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DOCUMENT NO D6-20609

TITLE: POSSIBILITIES AND DEVICES FOR THE SUPPRESSION OF JET NOISE

MODEL RESEARCH

ISSUE NO. 23 TO: DDC (DATE)

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Note: Most of the experimental information contained in this paper has been obtained from Boeing Documents and Technical Notes pertaining to past and current research on jet noise and jet noise suppression.

SUMMARY

This paper is based on a talk given by John B. Large on February 1, 1968, at the University of Tennessee Space Institute. The talk was part of a short course on noise generation and suppression in aircraft.

The paper discusses the present state of the development of techniques for the suppression of jet noise. The theoretical models on jet noise are mentioned briefly, and the "design principles" for jet noise suppressors are discussed in detail. In defining the generation of jet noise, the following three separate velocity regimes are considered:

(a) V^6 Regime (low speed jets)
(b) V^8 Regime (moderate speed jets)
(c) V^3 Regime (high speed jets)

The discussion on jet noise suppression considers each velocity regime separately, taking into account the extensive overlap between the regimes.

POSSIBILITIES AND DEVICES FOR THE SUPPRESSION OF JET NOISE

I. Introduction:

The subject of discussion in this paper is jet noise suppression. We will start off by defining what we mean with "suppression of jet noise." Jet noise refers to the broad-band acoustic radiation from the exhaust of a jet engine. Whereas the noisiness of the radiation depends on the subjective reaction of the individual listener, we, as engineers, use a standard, weighted integral of the radiation spectrum to arrive at an annoyance value of the noise. Suppression of jet noise therefore indicates a reduction in the acoustic power output from the jet in such a manner that a lower annoyance value results. The acoustic radiation in the near field of the jet causes a considerable loading on the aircraft skin, and we may define near field suppression as a reduction in the overall sound pressure level. It is significant to note that, ideally, the suppression must be accomplished without any reduction in the mechanical power of the jet.

The problem of jet noise suppression has existed for quite a few years. It first came up in connection with the development of large turbojet engines during the early 1950's. A considerable amount of work on suppressor nozzle design and development was accomplished by the aircraft and jet engine manufacturers from that time until the end of the decade, at which time the concept of turbofan engines became a reality. These engines offered a significant relief of the jet noise problem. A

Recent events have resulted in renewed effort to tackle the problem of jet noise suppression. It was realised that the high velocity afterburning engines for the supersonic transport aircraft could create a rather high noise level, and noise suppression devices would therefore seem a desirable complement to these engines. Consequently, Boeing is carrying out a development program aimed at suppressing the noise from high velocity engines. A

The establishment of stringent noise restrictions at major airports in the U. S. and Europe, and the simultaneous development of more powerful turbofan jet engines have led to attempts at suppressing the noise from low velocity jets. This development must, of course, be accompanied by efforts to reduce the compressor and turbine noise in turbofan engines. However, the lower frequency jet noise dominates the sound field during a majority of aircraft operations. Figures 1 and 2 show the perceived noise levels caused by the individual noise sources on a typical medium range turbofan-powered aircraft. The jet noise is seen to dominate at the higher thrust settings and at greater distances from the aircraft.

II. Jet Noise Generation and Suppression:

A. Theories on Jet Noise Generation

It is not the intent to give a discussion of the theories of jet noise generation mechanisms in this paper. A brief review is in order, however, so that we may indicate topics of present interest.

The works of Lighthill, Ribner, Ffowcs Williams, and several others appear to agree that in the jet velocity regimes of subsonic and low supersonic flow, jet noise radiation is dominated by sound generation of convected turbulence in the jet efflux. We call this the V^8 regime, because the total sound power emission varies with the eighth power of the flow velocity.

At higher supersonic flow, this relationship must necessarily fail, since otherwise we would be faced with the impossible situation of sound power emission exceeding the available mechanical power of the jet. We can therefore state as a fact that an upper limit for jet noise radiation as a function of velocity will approach a third power relationship at high velocities. Theoretical developments on supersonic jets by Ribner and Ffowcs Williams predict Mach wave radiation from the jet, increasing in intensity as the third power of velocity. An additional source of noise is the interaction between turbulence and the stationary shock pattern in supersonic jets. The question of which mechanism dominates the noise radiation will be considered later in this paper.

The noise from jets at low flow velocities has been discussed mainly by Ffowcs Williams. Depending on the roughness of the flow upstream of the jet nozzle exit, "dipole" noise generated in this region may overwhelm the "quadrupole" noise up to a nozzle exit velocity of 1000 ft/sec for cold flow. We call this the V^6 regime, because the total sound power varies with the sixth power of the flow velocity. As we will discuss later, this internally generated noise is of interest in the suppression of jet noise from turbofan engines.

To summarize, we may consider three separate velocity regimes in defining the noise generated by turbulent jets. Turbojet engines developed during the 1950's operate in the velocity regime dominated by V^8 noise. The engines used in current SST designs will operate at supersonic jet exhaust velocity in the transition regime between V^8 and V^3 dominated noise emission. Finally, high bypass ratio turbofan engines currently being developed operate at subsonic jet exhaust velocities just above the regime where V^6 noise becomes appreciable.

B. Relevance of Jet Noise Theory to Suppression

We may now pose the following question: How do we apply the theories of jet noise toward suppressing the noise from a particular jet engine? If we, for example, consider Lighthill's expression for acoustic power emission from subsonic jets,

$$\text{Acoustic Power} = \frac{K \rho_1^2 A V^8}{\rho_o a_o^5}$$

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we realize that the only free parameter is the unknown constant, K which depends on the level of turbulence in the jet. Lighthill's power law is consequently of very little help as a guide to the engineer. In order to emphasize this point, we apply the formula to a multitube suppressor nozzle with N tubes of equal cross-sectional area. According to arguments by Ribner and Ffowcs Williams, the total noise per unit length is greater by a factor $\sqrt{N}$ than the corresponding value for a single jet, so that the multiple jet produces as much power in its initial mixing region (of length proportional to $D/\sqrt{N}$, where D is the jet diameter) as does the single jet in its $\sqrt{N}$ times longer mixing region. Now, a multiple-nozzle suppressor is known to reduce the jet noise emission, so the theory is apparently inadequate in this application. We will return to this point later in the paper.

The lack of clear theoretical guidelines has forced the study of jet noise suppressors to rely on intuitive ideas and parametric investigations. Certain design principles have evolved from the almost countless suppressor nozzle configurations which have been tested over the years. None of these principles is well understood or documented, and a number of conflicting explanations of the physical mechanisms involved have been advanced.

In the following sections of this paper we will examine various classes of suppressor nozzles. The design principles which have been invoked will be discussed, and an attempt will be made to explain the mechanisms involved in the suppression of the noise.

III. Suppression of Jet Noise:

In the discussion above, we divided our treatment of the jet flow into three separate velocity regimes, each characterized by a dominant noise-generating mechanism. It will be convenient to maintain a similar separation when examining jet noise suppression methods, even though the velocity regimes overlap to such an extent that the dividing lines may appear rather artificial.

The pioneering work on jet noise suppression during the 1950's dealt almost exclusively with jets operating in the V^8 regime, and it will be appropriate to consider this regime first.

A. Jet Noise Suppression in the V^8 Regime

Before going on the describe methods of jet noise suppression, we must discuss the following question: Which part of the jet flow should we tackle in order to obtain optimum noise suppression? Or, stated more explicitly: Where in the jet are the prime sources of noise located? Since we are examining the V^8 regime, we restrict our discussion to quadrupole noise generation. It turns out that there are two main, opposing opinions on the problem.

The more commonly accepted point of view, advanced by Ribner, is that the dominant sources of [illegible] are located in the mixing region of the

jet. In the fully developed part of the jet, the noise generated per unit length varies inversely with the seventh power of the distance from the jet exit. The noise generation in the transition region and the fully developed jet is assumed to decrease gradually with distance downstream, as shown in Figure 3. Some experimental evidence for this point of view has been obtained by Mollo-Christensen in a carefully controlled experiment in which he measured the pressure field just outside the jet boundary as a function of the distance downstream from the jet exit.

In a recent unpublished work, Ffowcs Williams argues that matching the two curves of sound output per unit length in the mixing region and the fully developed jet, as in Figure 3, may be misleading. He suggests that since we do not know the relative values of the noise generated from the two regions, an equally plausible distribution is the one shown in Figure 4. If this is indeed the case, then the dominant sources of noise could be found in the region between 10 and 20 diameters downstream from the nozzle exit. Recent experiments by Potter and by Maestrello appear to support this point of view. In particular, Maestrello's results indicate that the sound sources of maximum intensity are located at least 10 nozzle diameters downstream from the jet exit. Both the theoretical and experimental considerations involved in determining this problem are still under study.

In view of this, it is not possible to reach a definite conclusion as to the location of the dominant sources of noise in the jet. In the following discussion, whenever an attempt is made to explain the mechanisms underlying the design principles, the uncertainty must be kept in mind.

1. Mixing Nozzle Jet Noise Suppressors: The name "mixing nozzle" refers to the large class of suppressors which presumably operate on the principle of entraining surrounding air into the jet flow in order to shorten the mixing region and to reduce the mean velocity gradients. This class includes multitube nozzles and multilobe or corrugated nozzles. Examples of mixing nozzles are shown in Figures 5 and 6. In designing mixing nozzles for optimum noise suppression, we apply three main principles: (i) Jet exit geometry, (ii) Ventilation (access of secondary air to individual jet streams), (iii) Flow break-up (number of individual jet streams).

In applying these principles, we must remember that the suppression has to be accomplished with a minimum performance loss of the engine. Each of the principles of suppression requires for its complete and separate definition a good deal more information than is presently available. Even so, they have assisted in the design of suppressors which cause the total acoustic power generated to drop to one-thirtieth of the unsuppressed noise, or a 15 dB reduction.

(i) Jet Exit Geometry - In Figure 7 we have defined some of the parameters of interest in the design of mixing nozzles. We have shown a multitube nozzle, and in the following discussion we will restrict ourselves to this kind of mixing nozzle, with the understanding that

the arguments may be easily generalized to include multilobe nozzles. One important parameter is the area ratio, which we define as the ratio of the area circumscribing the mixing nozzle to the area of the original jet nozzle. Increasing the area ratio leads to an increase in the rate of secondary air mixing. This promotes the development of the self-preserving jet closer to the nozzle exit, so that low frequency noise suppression results from the shortening of the transition region. We know that a maximum amount of noise suppression occurs when the spacing between the individual nozzle elements approximately equals their diameter, causing the jets to interfere at the end of their mixing regions. This criterion would seem to define an optimum spacing, or area ratio. As the area ratio is increased further, we quickly reach the point at which the elements are so widely spaced that they behave like individual jets. The sum of their acoustic powers is then equal to that from the single primary jet, so that the only effect is the shift in the characteristic frequency of the noise.

As it turns out, however, the optimum area ratio is not unique. It varies with the geometrical arrangement of the tube elements, and increases with an increasing number of jets, as shown in Figure 8. One reason for this effect is that as the number of tubes in the suppressor nozzle increases, it becomes more difficult to provide good access of secondary air to the center part of the nozzle. Consequently, it is necessary, when the number of tube elements is large, to increase the spacing between the elements to a value beyond the optimum in order to provide good ventilation.

(ii) Ventilation - For simple cases, it is possible to compute the cross-sectional area needed for adequate secondary air access to divided nozzle elements from theoretical considerations of jet mixing requirements. However, this computation becomes less accurate when it is applied to hot jets, or to a mixing nozzle with complex elemental nozzle terminations.

It has been maintained that access of secondary air to every jet stream issuing from the nozzle should be as good as possible. The effect of "starvation" on noise suppression, however, is known only in a qualitative way. Figure 9 illustrates an experiment by Rolls-Royce on ventilation effects. The graph shows the variation with jet velocity of the noise from a hexagonal array of 55 nozzles, and a square array of 48 nozzles, compared with that from a single circular nozzle of the same total area. Despite its smaller area ratio and smaller number of jet elements, the square array gives the greater attenuation. This must be attributed to the easy access of secondary air to the center of the square array in comparison with the relatively poor ventilation of the hexagonal array.

Recent investigations by Boeing have shown that the effect of ventilation on the noise suppression diminishes as the jet velocity is increased, and becomes negligible at jet pressure ratios above approximately 2.0 to 2.5. Figure 10 shows the perceived noise suppression achieved with a five slot nozzle as the secondary air access routes are

increasingly blocked off. At jet pressure ratios of 2.6 and 3.0 the effects of ventilation are practically negligible, whereas, at a jet pressure ratio of 1.8 there is a great loss in the noise suppression as ventilation is reduced. Figure 11 shows this to be due to an increase in high frequency noise, which is presumably generated close to the nozzle exits.

One effect of ventilation, however, is maintained even at high jet pressure ratios. The loss in measured jet thrust increases significantly as the secondary air access is blocked. This can be accounted for from consideration of the base drag.

(iii) Flow Break-Up - Break-up of the flow into a number of individual jet streams by means of multitube or multilobe nozzles has been shown to result in large amounts of jet noise suppression. This result is subject to the condition that the spacing between the individual jet elements be approximately equal to their diameter, in the case of circular elements, or their width, in the case of lobe elements.

We will illustrate the effect of flow break-up by considering multitube nozzles of constant area ratio, but with an increasing number of flow tubes. Figure 12 shows the variation in the jet noise spectra. It appears that two main effects result from increasing the number of flow elements. The dominant region in the noise spectrum is seen to shift to higher frequencies with an increase in the number of tubes. This is accompanied by a continuous drop of the high frequency part of the spectrum until, for the hypothetical case of an infinite number of tubes, the high frequency part no longer dominates. The sound suppression in the low frequency part of the spectrum appears to be independent of the number of tubes.

(iv) Total Noise Suppression - We will attempt to explain the noise reduction mechanisms which cause these changes in the noise spectra, keeping in mind our uncertainty as to the location of the dominant sources of noise in the jet. In general, however, we may assert that the high frequency noise is generated closer to the nozzle, and the low frequency noise further downstream in the transition region and in the fully-developed jet. Depending on the point of view, the dominant frequency region in the noise spectrum is generated either at the end of the potential core or well into the transition region of the jet.

Referring back to Figure 7, we may now argue that a multielement jet contains two separate regions where mixing takes place. One is the mixing region of the elemental jets close to the nozzle exit. These jets coalesce into a single jet flow which possesses a larger scale mixing region. The frequencies of the noise generated in each region scale with the Strouhal number fD/U, where D is the diameter of the elemental jets and the diameter of the coalesced jet, respectively. Low frequency noise is generated in the mixing region and the transition region of the latter. It appears that an increase in the area ratio of the nozzle will have two effects on this noise-generating region. The characteristic frequencies of the noise will be lowered

as the area ratio increases. This effect is augmented by the increased rate at which the jet flow velocity is reduced. Increasing the area ratio also leads to greater rate of mixing with the surrounding air, promoting the full development of the jet closer to the nozzle exit. The consequent shortening of the mixing region and the transition region of the coalesced jet account for the suppression of the low frequency noise.

The characteristic frequencies of the noise generated in the mixing region of the elemental jets will increase as the diameter of the jets is reduced. This accounts for the frequency shift of the dominant part of the spectrum with increasing numbers of flow tubes, as shown in Figure 12. The suppression of the high frequency noise is more a matter of conjecture. We know that increasing the spacing between the elemental jets leads to an increase in the high frequency noise. Presumably, this results from the increased length of the independently acting elemental jets. It has been suggested that, at some optimum spacing, the secondary air induced between the jet elements causes noise suppression by reducing the mean shear in the jets. This view is partly substantiated by the experimental observation that blocking off the secondary air access increases the high frequency noise generation (Figure 11). However, as we discussed in an earlier section, this effect decreases with increasing flow velocity and apparently does not occur at jet pressure ratios above that at which the flow is choked. Another possible suppression mechanism is the shielding of the high frequency noise, generated by the elemental jets in the center of the flow, by the circumferential jets.

2. Other Jet Noise Suppressors: Having considered mixing nozzle suppressors rather thoroughly, we will now go on to a brief discussion of suppressor nozzles which rely on separate or additional techniques to achieve a reduction in the acoustic power output.

(i) Directional Nozzles - We define a directional nozzle as a sound suppressor which operates partly or completely on the principle of redirecting the acoustic radiation. It has been determined experimentally that the noise radiation pattern from a slot or rectangular nozzle is elliptical about the jet axis. The significance of the elliptical noise pattern becomes apparent if we recognize the requirement of a suppressor in terms of its operational use. While it is desirable to achieve large noise reductions in all directions and under all operational conditions of an aircraft, the primary aim is to suppress the noise radiated toward the community as the aircraft flies over.

In the past, several investigations into the noise-suppressing qualities of slotted nozzles have been conducted. Figure 13 shows the results obtained with one particular type. It is of interest to note that, in addition to the considerable noise suppression in the direction normal to the short ends of the nozzle, there is also a reduction in the total acoustic radiation. We may reformulate the design principles of noise suppression to state that a reduction in the sound power

can be obtained by an increase in the mixing perimeter of the jet nozzle. The pronounced directionality of the radiation is not so easily explained. Tests show that the high frequency noise is markedly more elliptical than the low frequency noise, suggesting that the directional effects are mainly limited to the jet mixing region. Due to the shape of the nozzle exit, the jet initially expands considerably more off the short sides than off the long sides of the nozzle. This results in a large flow region of high mean shear radiating high frequency noise off the long sides, whereas the low mean shear in the rapidly expanding short side mixing region reduces the high frequency radiation off the short sides of the jet wake.

(ii) Ejectors - An ejector system is primarily a thrust-augmentation device. The jet discharging from the primary nozzle mixes with the entrained airflow within the cylindrical shroud, resulting in an augmented jet of lower velocity. If we consider the acoustic power output of a jet to vary as the eighth power of the flow velocity, the ejector system seems very attractive for the purpose of suppressing jet noise.

Investigations have shown, however, that an excessive ejector length is required in order to promote sufficient mixing for a significant noise reduction. Middleton's results from testing a simple conical nozzle with ejectors of increasing length, shown in Figure 14, suggest an ejector length of the order of 20 nozzle diameters.

The mixing of primary and secondary air will be increased considerably by using ejectors in combination with mixing nozzles. The ejector length required for satisfactory mixing under these conditions may be reduced to two or three nozzle diameters. Such ejector systems have been found to cause a noise suppression of 3 - 5 db beyond that achieved with the mixing nozzle alone.

We will return to a discussion of ejector systems later in this paper in connection with suppression of noise from high velocity jets.

(iii) Shielding - A test program has been conducted at Boeing to determine the effect of shielding panels placed parallel to the jet efflux on the acoustic radiation from the jet (Figure 15). The results have implications regarding the effectiveness of possible shielding suppressors, or the effect of nearby aircraft sections in reducing the noise levels in a specified direction.

It was found that in order to obtain pronounced shielding of noise, the panel must extend past the nozzle exit plane by no less than eight diameters. This length can be reduced to four diameters for the same amount of suppression, however, when a mixing nozzle suppressor is used in combination with the shield (Figure 16). As expected, the panel proved to be a more effective shield for the high frequency noise. This is clearly indicated by the noise spectra in Figure 17. The increased effectiveness for the mixing nozzle is due to the fact that the peak of the noise spectrum is shifted to higher frequencies.

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(iv) Annular Flow Nozzles - The development of the bypass jet engine suggested the possibility that annular flow might, under some conditions, affect the jet acoustic power output advantageously. One may infer, on the basis of Lighthill's theory, that the noise generation depends primarily on the mean velocity gradients in the flow. The introduction of a low speed flow surrounding the primary jet will reduce the velocity gradients significantly, and ought to result in a lower acoustic power output.

The results from a model scale experiment designed to verify these assumptions are shown in Figure 18. At low values of the secondary flow velocity, the effect on the noise generated by the primary jet is negligible. At high values of the velocity ratio, the noise generated by the secondary flow becomes appreciable. However, at intermediate velocity ratios, the perceived noise level values are significantly lowered, indicating a noise-suppressing mechanism of the type discussed above.

Further experiments have investigated the effect of staggering the exits of the primary and secondary flows. It was found that most of the noise suppression disappeared when the secondary exit was withdrawn more than one nozzle diameter behind the primary exit plane.

3. 259-Tube Suppressor:

A full-scale multitube nozzle suppressor has been designed and tested by Boeing to determine if the same large amounts of jet noise suppression could be obtained full scale as has been demonstrated in small model tests. The suppressor consisted of an array of 259 identical tubular nozzles, coplanar, uniformly spaced, and provided with adequate ventilation space for the flow of secondary air between tubes, as shown in Figure 19. In addition, several acoustically lined cylindrical shrouds were tested in conjunction with the multitube suppressor in order to investigate further the effect of high frequency noise shielding. Figure 20 shows the multitube nozzle surrounded by a 10-ft. long lined shroud. The main test results are shown in Figures 21 and 22. Examination of Figure 21 shows that the principal effect of the multitube nozzle is a very large decrease in noise level in the middle frequencies, a substantial decrease in the low, and little or none in the high. The addition of acoustically lined shrouds reduces the high frequency noise greatly. Figure 21 also shows that the effect of an unlined shroud is negligible. Conversely, the lined shroud does not reduce the noise level from the standard nozzle. This result is to be expected in view of our earlier discussion on ejector systems.

4. [illegible] V^3 - V^8 [illegible]

Two distinct mechanisms of noise generation are characteristic of high velocity jet flows. The first is the Mach wave radiation from turbulent

eddies convected at supersonic velocities with respect to the speed of sound in the ambient medium. This radiation is strongly directional, emitting from the jet at an angle of $\Theta = \cos^{-1} c_o/V_c$, where V_c is the convection velocity of the eddies. The second mechanism is the generation of sound through the interaction of the turbulence with stationary shock waves which are formed in over-expanded or under-expanded supersonic jets.

Acoustic measurements with jets at high supersonic velocities clearly indicate the dominance of the Mach wave radiation. However, our knowledge is very limited when we attempt to predict which noise-generating mechanism dominates at low supersonic Mach numbers. Ribner's theory of turbulence-shock wave interaction is not yet sufficiently developed to permit a realistic appraisal of the intensity of the noise generated by this mechanism. The most convincing evidence of its importance has been found in shadowgraph pictures of supersonic jets, in which strong acoustic radiation is seen to emanate from localized shock regions in the flow. Disregarding the shock-induced noise for the moment, it is clearly evident that there is a velocity of transition at which the quadrupole noise ceases to dominate, and Mach wave radiation becomes important. We must here consider Ffowcs Williams' argument that, whereas quadrupole noise is directly proportional to the cube of the turbulent eddy scale, and inversely proportional to the fourth power of the eddy time scale, Mach wave radiation, on the contrary, is inversely proportional to the square of the eddy scale and directly proportional to the time scale. Consequently, changes in turbulence scales which alleviate the quadrupole mode aggravate the Mach wave case and vice versa. This feature raises the possibility that suppressors known to be good at subsonic speeds might well be very poor at high supersonic speeds.

1. Mixing Nozzle Jet Noise Suppressors - We will discuss the results from two sets of tests with scale model mixing nozzle suppressors in an attempt to substantiate the arguments of the preceding section.

The first investigation was conducted with a six-lobe corrugated nozzle of area ratio 1.6. The measured perceived noise level suppression relative to standard nozzle is shown in Figure 23 as a function of the nozzle exit velocity. The suppression is seen to increase with increasing velocity up to a jet velocity of 2000-2500 ft./sec., which corresponds to sonic eddy convection velocity with respect to the sound speed of the surrounding air. At higher velocities, the suppression decreases rapidly with increasing jet velocity.

The second set of tests was conducted with a 37-tube suppressor nozzle of area ratio 4.65, in which each elemental tube ended in a corrugated nozzle. Figure 24 shows the measured suppression plotted vs. the nozzle exit velocity. It is apparent that, in this case, the high suppression is maintained as the velocity increases beyond 2500 ft./sec.

We attempt to explain the improved high velocity performance of the [illegible] suppressor in the following manner. The large rate of mixing achieved with this configuration results in a rapid decrease from the initial flow velocity. As long as the velocity of the augmented flow remains less than approximately 2500 ft./sec., we may expect the nozzle to maintain its suppression characteristics. It is, therefore, apparent that the limiting factors for the use of mixing nozzle suppressors in high speed jets reduce to the permissible penalties in aerodynamic drag and nozzle weights.

B. Ejector Nozzle Suppressors - In the preceding sections we have discussed the emergence of high speed noise-generating mechanisms at jet velocities of approximately 2500 ft./sec. It appears that in order to gain any noise suppression from break-up of a high speed flow, we must simultaneously affect a considerable reduction in the flow velocity. This notion is implicit in the development of noise suppressors for the SST engine. We have mentioned earlier in this paper that the use of ejectors in combination with mixing nozzles greatly increases the mixing of the primary jet and secondary air, resulting in a reduced velocity augmented flow. The high temperature of the SST engine jet exhaust makes the use of a mixing nozzle a complicated engineering problem, and therefore, the initial suppressors to be used on the SST may consist of a series of retractible chutes projecting into the flow from the ejector walls. Figure 25 shows test results from such a configuration. In this particular case, the nozzle-ejector combination produces as much noise as the nozzle alone, but with the chutes inserted, a 9 PNdB suppression is obtained.

C. Jet Noise Suppression in the V^6 - V^8 Regime

It has been observed experimentally that with rough flow conditions upstream of the nozzle of a low velocity jet, the acoustic power generation varies with the sixth power of the jet velocity. This implies that, in addition to the V^8 sources of noise, there exists a noise-generating mechanism of lower power of velocity, which dominates the sound field for jet flows of high turbulence and low exit velocity. Ffowcs Williams has discussed several possible mechanisms of dipole noise-generation inside the jet nozzle, and suggests that the most probable mechanism involves the turbulence in the nozzle exit plane, giving rise to dipole sources which radiate with an acoustic efficiency of

$$\eta_d \sim \frac{\alpha^2}{6\pi} \rho_j/\rho_o M^3$$

If we assume the V^8 noise-generating efficiency to be

$$\eta_q \sim 10^{-4} \rho_j/\rho_o M^5$$

The V^6 noise will dominate the sound field below a jet exit velocity of [illegible]. For a [illegible] turbulence level, this is a speed of [illegible] ft./sec.

As an example, for an engine having a jet exhaust velocity of approximately 1900 ft./sec. at maximum thrust, the V^8 noise will be 5 dB higher than the V^6 noise, according to the above assumptions. High bypass ratio turbofan engines currently being developed have a primary jet exhaust velocity of approximately 1250 ft./sec., at which speed our calculations show both sources of noise to be of equal magnitude.

We must admit that the preceding calculations are based on order of magnitude estimates only, and could be in error by a considerable factor. Some experimental evidence, however, has been obtained in tests with air jets in which the turbulence level upstream of the nozzle exit varied. Figure 26 shows the increase in the acoustic power emission with jet velocity from a model scale jet under two different upstream flow conditions. The case of smooth upstream flow shows a low noise level which increases as the eighth power of the jet velocity. With highly turbulent flow upstream of the nozzle, the noise level is much higher at low velocities than in the first case, and it increases as the sixth power of the jet velocity. The intersection of the two curves would identify the velocity above which the V^8 noise dominates.

Further evidence is found in tests with model scale suppressor nozzles. We refer back to the results in the low velocity region in Figures 23 and 24. The noise suppression decreases sharply as the jet velocity is lowered, both with the six-lobe corrugated nozzle and the thirty-seven tube nozzle, and in the first case, it even shows negative values in the low velocity region, indicating an increase in the generated noise.

We will tentatively conclude from the discussion above that our noise suppression design principles cease to be valid in the low jet velocity range because the generation of V^6 noise is not significantly affected by conventional noise suppressors. In the case of turbofan engines, this means that the maximum jet noise reduction possible with external suppressors is limited to the difference between the intensities of V^8 noise and V^6 noise. As we have discussed earlier, this difference is 5 dB for today's turbofan engines, and less for lower velocity engines.

It is not our intention to suggest that further improvements in the jet noise characteristics of turbofan engines are beyond the realm of possibility, but it appears that the value of external noise suppressors is limited unless the internal aerodynamic flow of the engine receives adequate consideration.

IV. [illegible] of Near Field Jet Noise

Whereas the noise generation from jet engines is usually considered in view of its effects upon the community, it also presents a problem

to the aircraft manufacturer. The loading on the aircraft skin due to near field sound pressure fluctuations can be considerable, and it may be necessary to increase the loading strength of the panels in the vicinity of the engines. The necessity of maintaining an acceptable noise level inside the aircraft fuselage leads to soundproofing problems. We expect, therefore, that noise suppression is also a desirable objective in the mind of the structural designer.

Acoustic measurements of jet engines operating in the V^8 velocity region show that the effect of jet noise suppressors is even more pronounced in the near field than in the acoustic far field. This result is quite as expected. We have shown earlier that mixing nozzle suppressors cause an upward shift in the characteristic frequencies of jet noise. The near field pressure is weighted heavily towards the low frequencies, so that a reduction in the lower part of the spectrum will have a greater effect in the near field than far away from the jet.

It is unfortunate that the same suppression effect is not present in high velocity jets. Tests with the chuted ejector for the J57 engine show the near field noise suppression to be considerably less than that obtained in the far field. This result is not immediately obvious, but it may be satisfactorily accounted for on the basis of our previous arguments about high velocity jets. We assumed that a dominant part of the noise field of the unsuppressed jet is due to Mach wave radiation and shock-turbulence noise. These noise sources do not possess conventional near fields, so we may assume that the near field of the unsuppressed jet is dominated by V^8 noise. In the suppressed jet, however, the two high-speed mechanisms have been partly eliminated, resulting in far field noise suppression without a corresponding reduction in the near field.

V. Testing of Jet Noise Suppressors

We have mentioned earlier that, because of the limitations and shortcomings of our suppressor design principles, we have to rely heavily on parametric studies in the development of noise suppressors. The high cost of full-size suppressor construction and testing lead to the use of scale model studies. The reliability of the test results obtained with scale model suppressors obviously depends on the accuracy of our scaling parameters, and in view of our earlier discussion, we may expect these parameters to become inadequate in the high and low jet velocity regimes.

In the V^8 jet velocity region, we have found satisfactory scaling to result in terms of the Lighthill parameter $P = K\rho_0^2 A V^8 / \rho_0 a_0^5$ and the Strouhal number $S = fD/V$. We test at the given jet velocity and jet temperature so that the only two variables are the area ratio

$$A(\text{full scale})/A(\text{model scale})$$

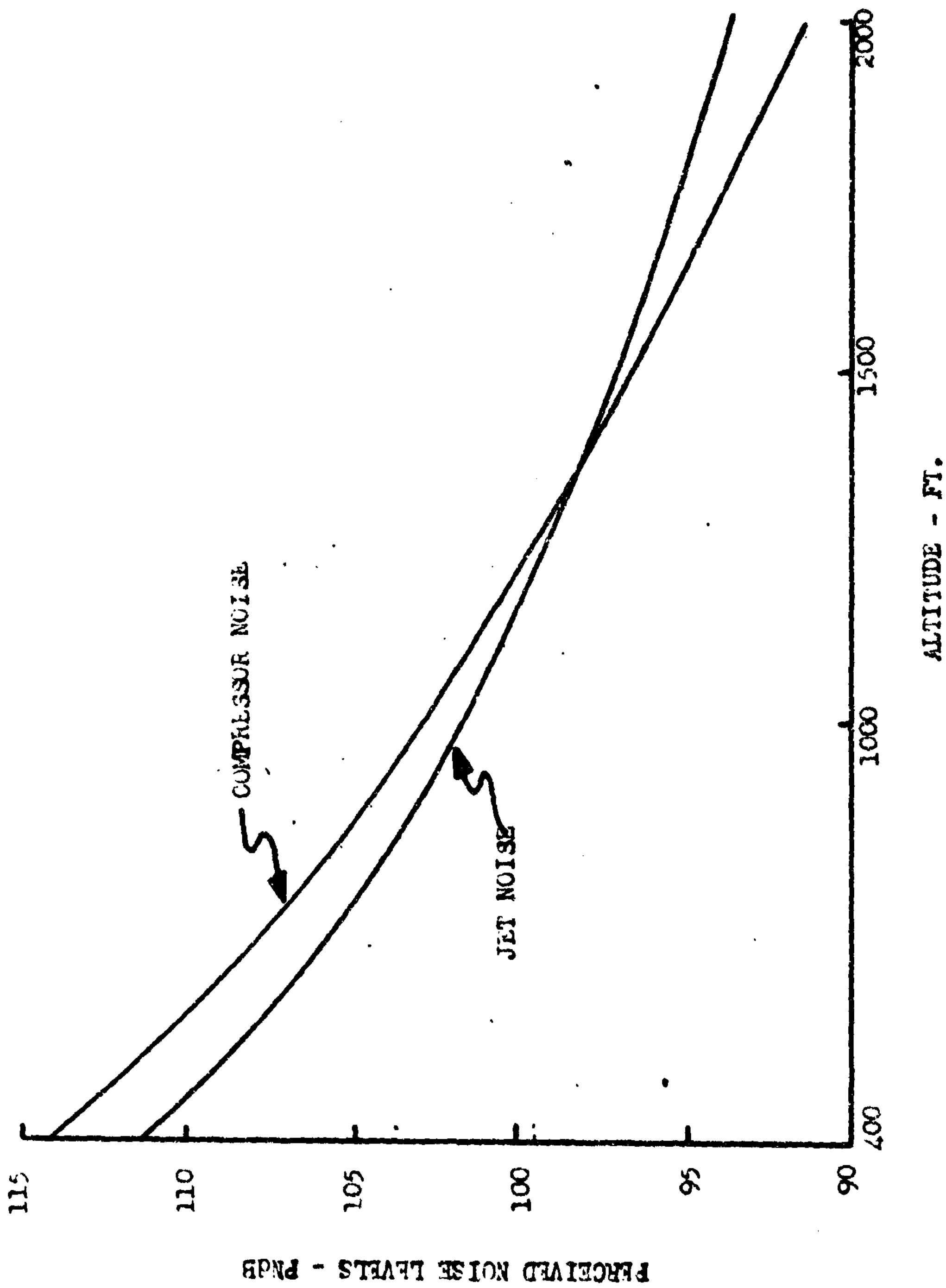
and the frequency ratio

$$f(\text{full scale})/f(\text{model scale}) = \sqrt{A(\text{model scale})/A(\text{full scale})}.$$

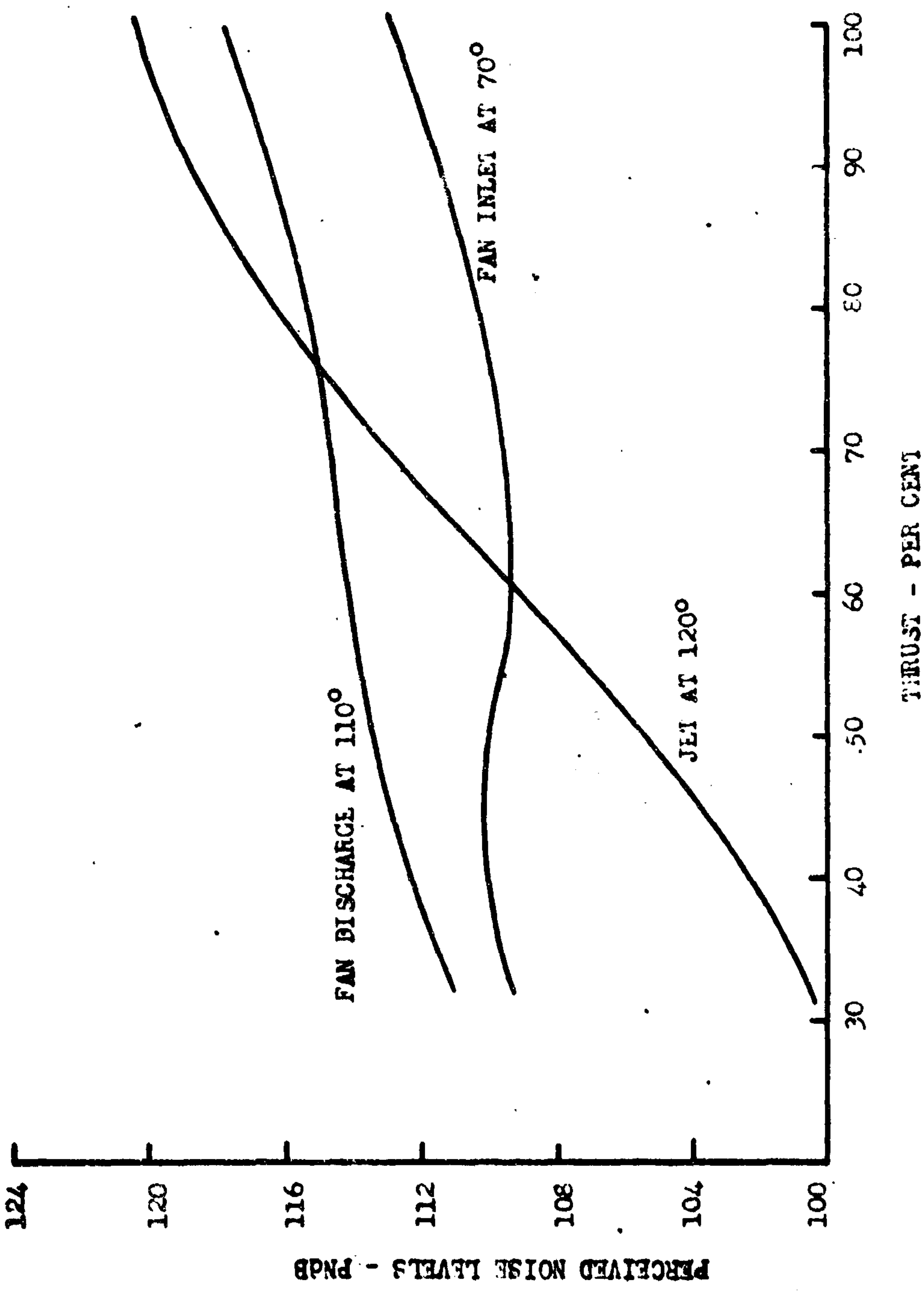
While we restrict ourselves to geometrical scaling of the external flow fields, we can also ensure the validity of our scale model results in high speed flow. At low jet velocities, however, these relations seem inadequate. It appears that we must match the turbulence level upstream of the engine exhaust in our scale model jets in order to account for the generation of V^6 noise. This added complexity may be overcome by testing with scale model jet engines, or by controlling the upstream flow conditions of the scale model air jet. As of now, the problem has not received adequate attention.

It has proved very difficult to construct complex scale model configurations which will maintain their shape during prolonged testing in high temperature jet flow. The possibility of testing at reduced velocity and temperature has therefore been considered. It is immediately apparent from Figures 23 and 24 that a velocity reduction cannot be permitted, since the jet noise reduction with a particular suppressor nozzle is strongly dependent on the jet velocity. A reduction in the jet temperature, while keeping the jet velocity constant, is more open to discussion. It is known that the rate of spread of a jet increases with increasing jet temperature. This has the effect of shifting the spectrum of the emitted noise; however, by a rather small amount. The angle of maximum radiation increases with increasing jet temperature, but again, this change is not large for a moderate temperature change. The main objection to reducing the flow temperature concerns the generation of noise by the high speed mechanism of shock wave - turbulence interactions. A temperature reduction causes an increase in the flow Mach number, and we are not in a position to predict the effect of the resulting change in the jet shock structure on the noise levels.

Referring again to Figure 24, we note that, although there is an apparently systematic spread in the suppression data with temperature variation, the spread is small in comparison with the total suppression. We may conclude that, for moderate temperature variations, the effect of jet temperature on the noise suppression characteristics of a nozzle is small enough to be neglected.



			REVISED	DATE		
CALC					VARIATION IN COMPONENT PNL WITH ALTITUDE FOR TYPICAL MEDIUM RANGE TURBOFAN-~~POWERED~~ AIRCRAFT	D6-20609
CHECK						FIG. 1
APPD						
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 23



CALC			REVISED	DATE	VARIATION IN COMPONENT PNL WITH THRUST FOR TYPICAL MEDIUM RANGE TURBOFAN-POWERED AIRCRAFT	D6-20609
CHECK						FIG. 2
APPD						
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 24

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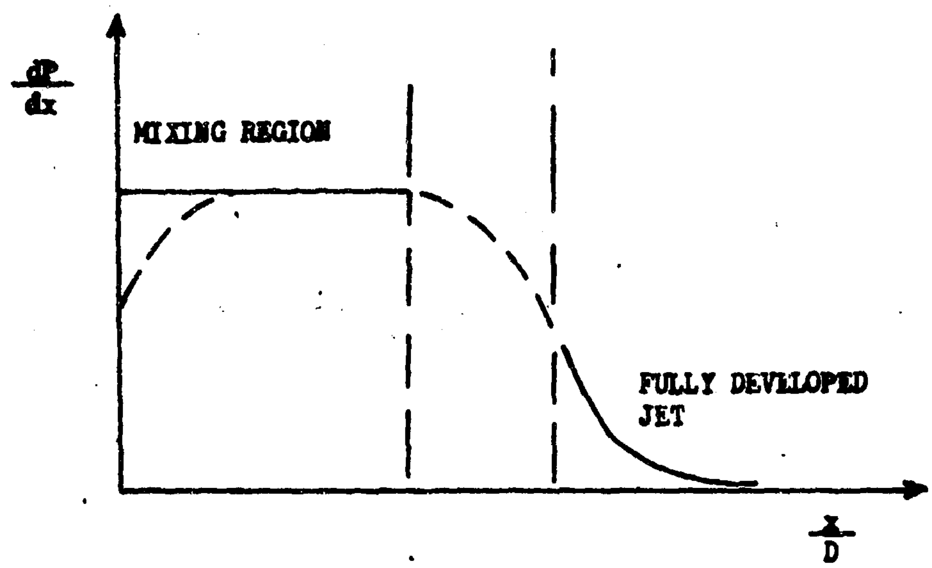
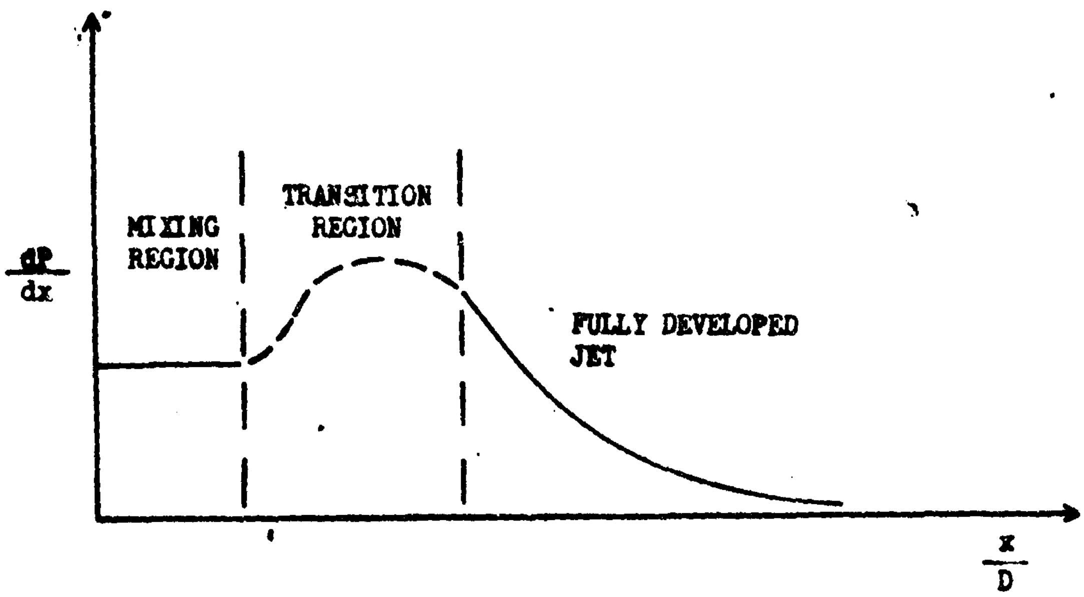
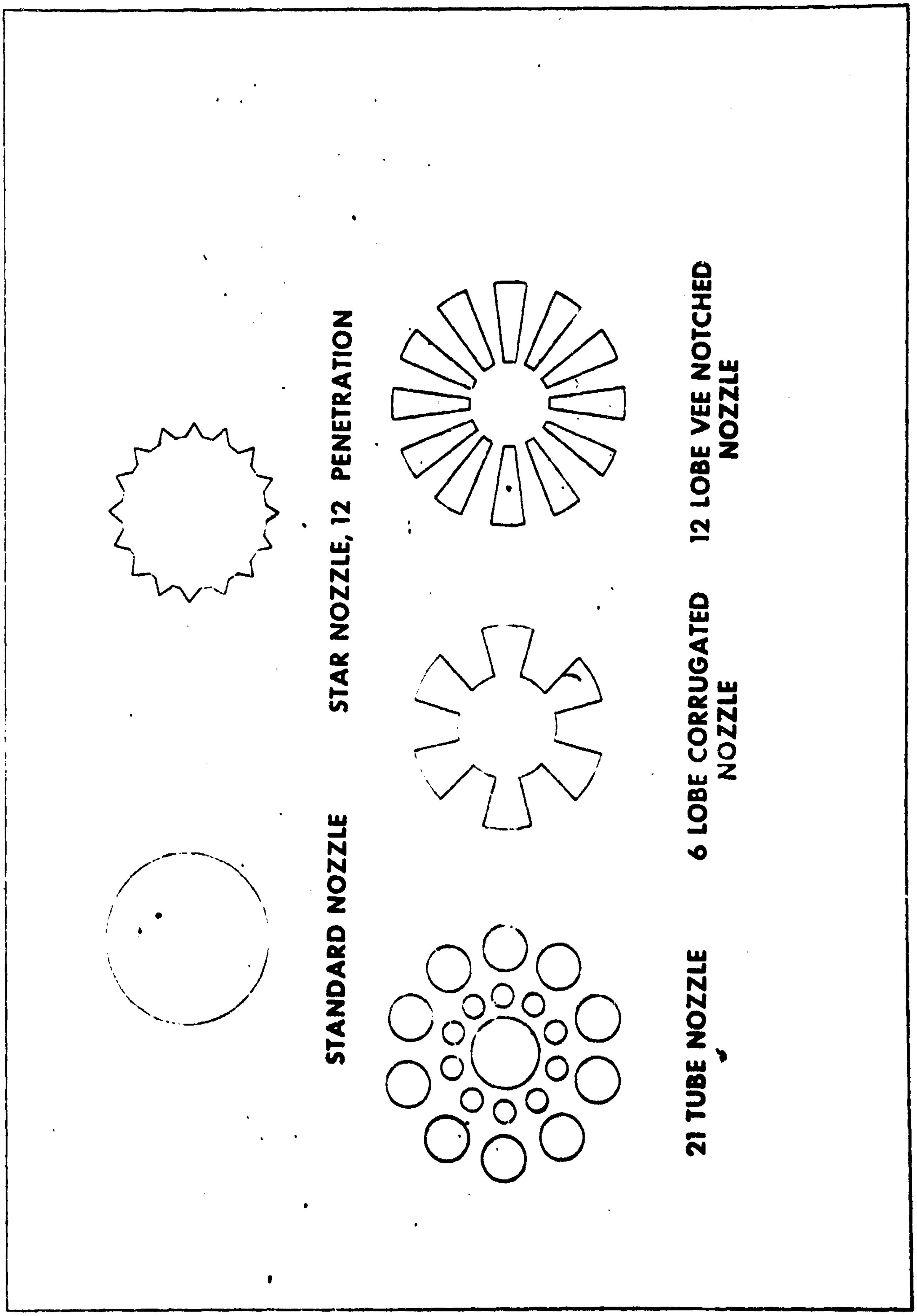
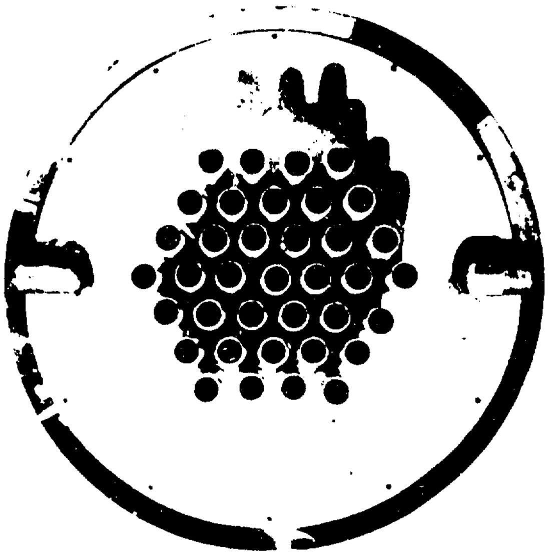


			REVISED	DATE	ACOUSTIC POWER OUTPUT PER UNIT LENGTH OF JET (RIBNER)	D6-20609
CALC						FIG. 3
CHECK					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 25
APPD						
APPD						

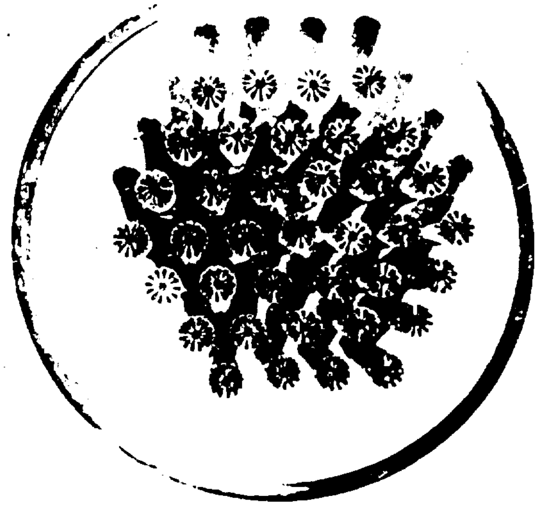


			REVISED	DATE	ACOUSTIC POWER OUTPUT PER UNIT LENGTH OF JET (FFOWCS WILLIAMS)	D6-20609
CALC						FIG. 4
CHECK						
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 26
APPD						

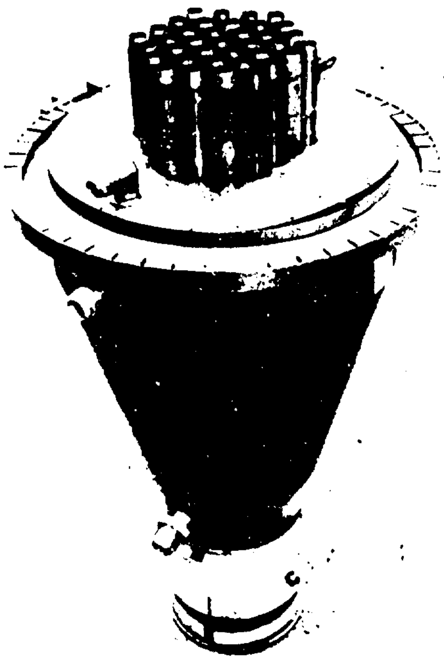

STANDARD NOZZLE
STAR NOZZLE, 12 PENETRATION
21 TUBE NOZZLE
6 LOBE CORRUGATED NOZZLE
12 LOBE VEE NOTCHED NOZZLE
AD 1546 D



ROUND CONVERGENT NOZZLE
AREA RATIO 3.33



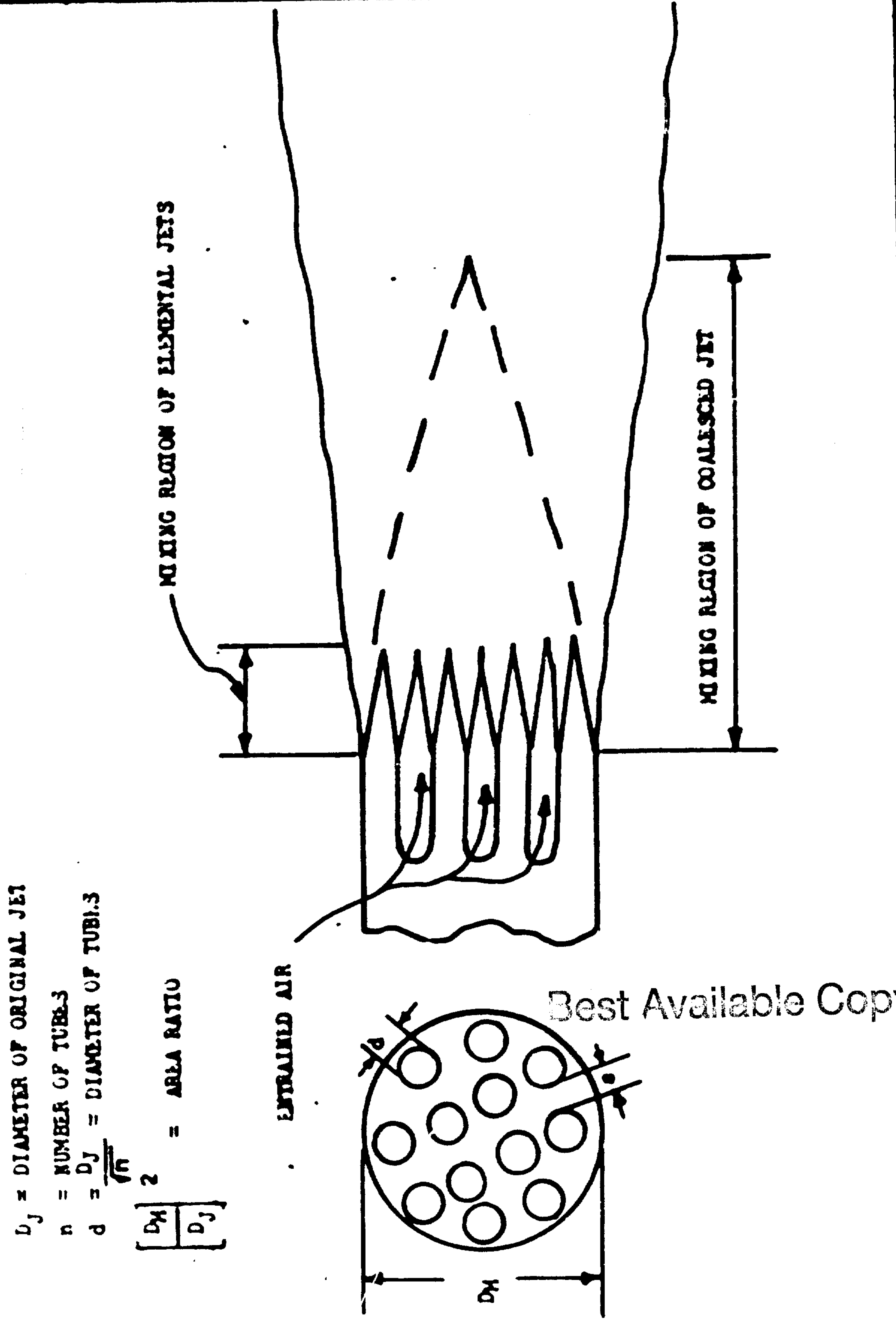
CORRUGATED NOZZLE
AREA RATIO 4.65



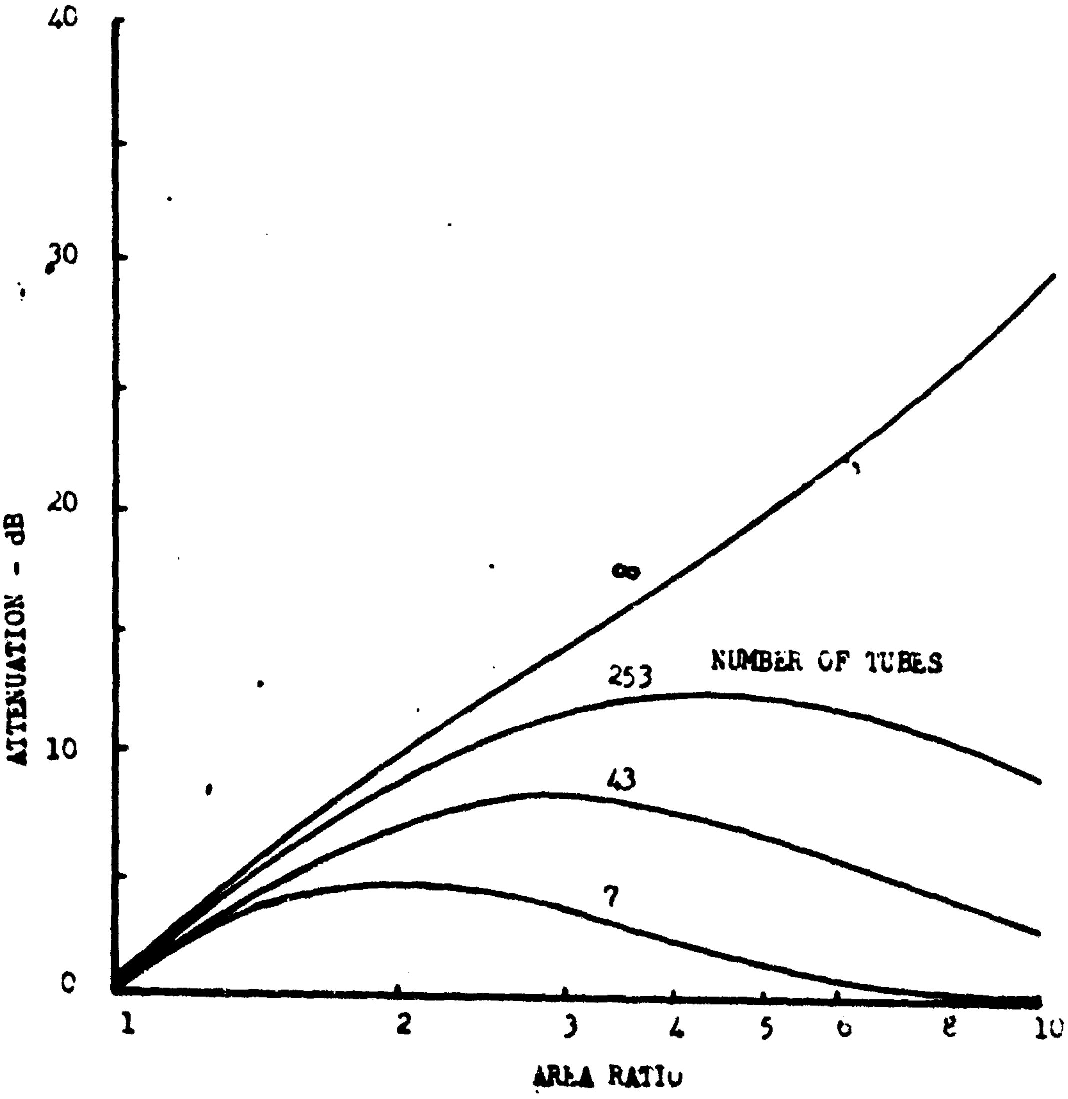
NOZZLE ASSEMBLY

CORRUGATED NOZZLE
AREA RATIO 7.25

37 TUBE NOZZLES



CALC			REVISED	DATE	SCHEMATIC OF JET FLOW FROM MULTITUBE NOZZLE	D6-20609
CHECK						FIG. 7
APPD						
APPD					THE BOEING COMPANY RENTON WASHINGTON	PAGE 29

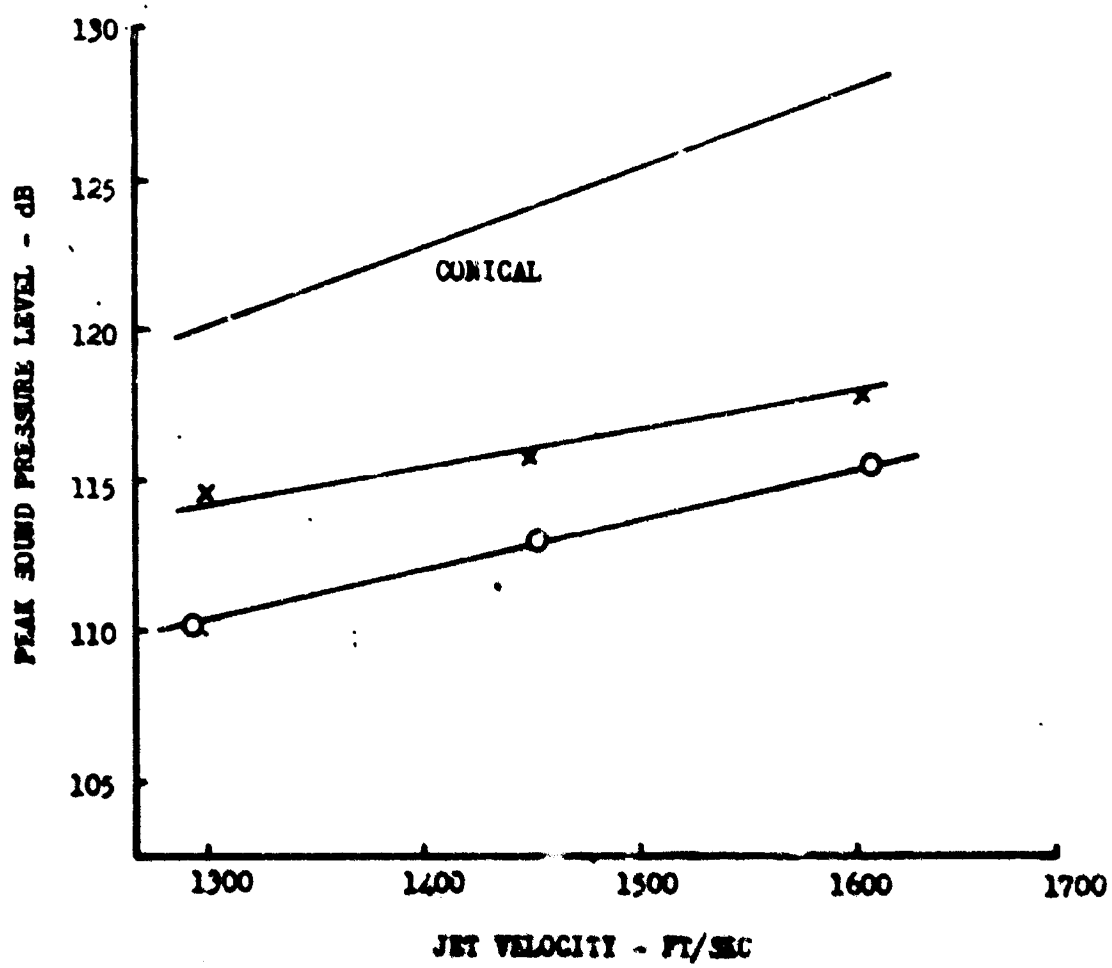


67½° FROM EXHAUST AXIS

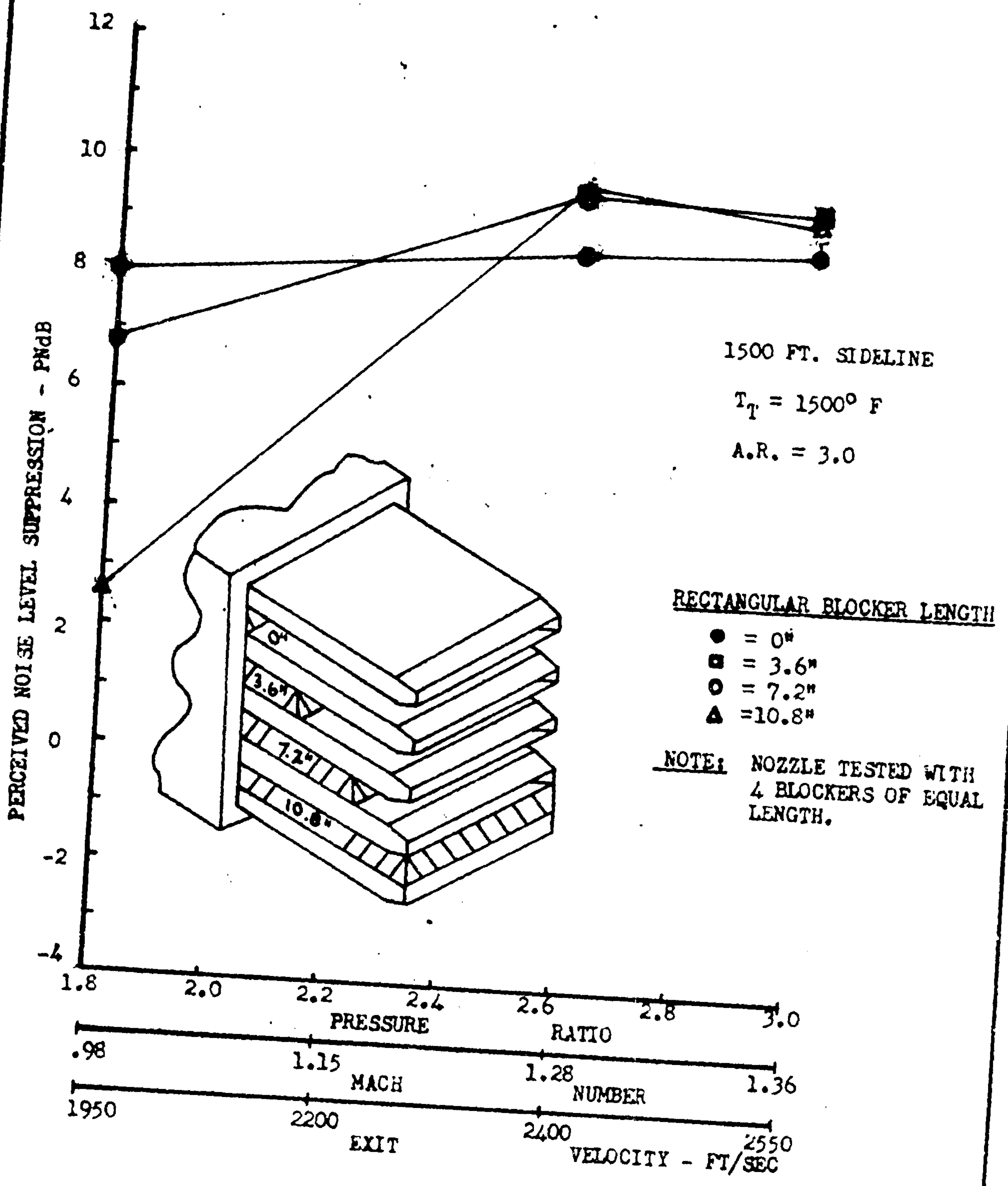
CALC			REVISED	DATE	VARIATION IN SPL SUPPRESSION OF MULTI-TUBE NOZZLES WITH NUMBER OF TUBES AND AREA RATIO	D6-20609
CHECK						FIG. 8
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 30
APPD						

X HEXAGONAL MULTITUBE ARRAY; A.R. = 6, $\frac{d}{D}$ = 0.135,
NO. OF TUBES = 55

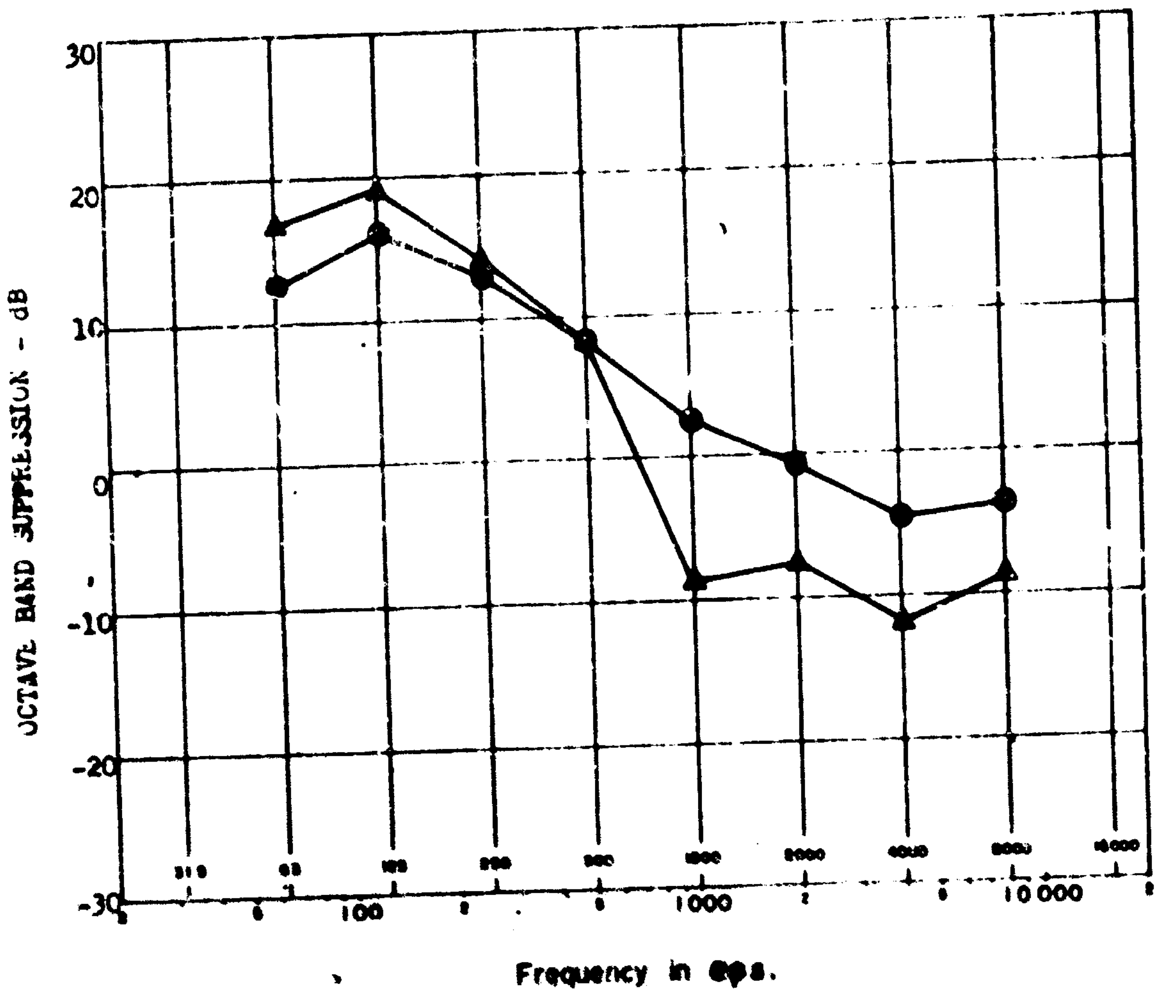
O SQUARE MULTITUBE ARRAY; A.R. = 4, $\frac{d}{D}$ = 0.145,
NO. OF TUBES = 48



CALC			REVISED	DATE	VARIATION IN SPL SUPPRESSION WITH JET VELOCITY OF TWO GEOMETRICALLY DIFFERENT MULTITUBE ARRAYS (GREA'REX).	D6-20609
CHECK						FIG. 9
APPD						
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 31

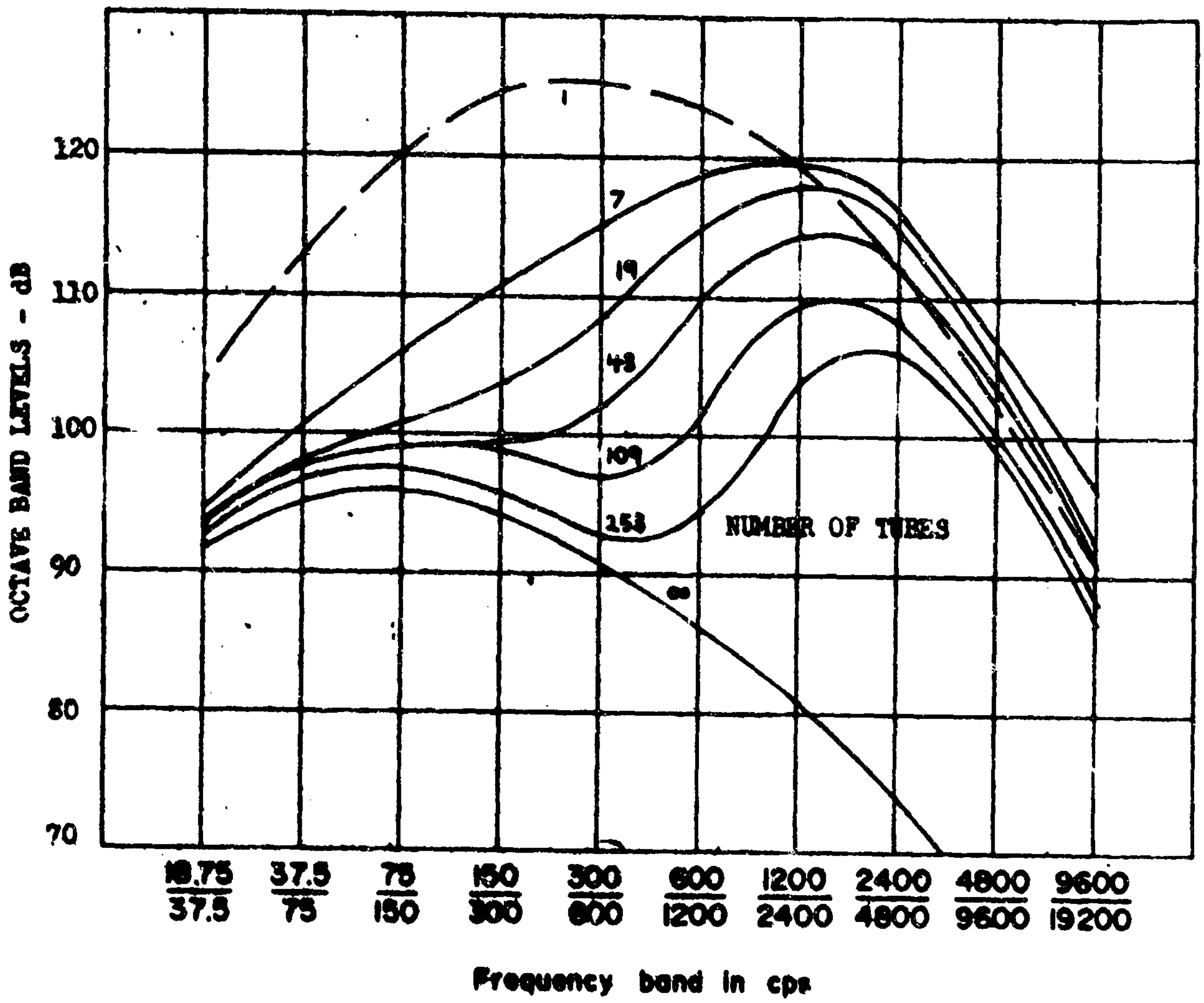


CALC			REVISED	DATE	VARIATION IN PNL SUPPRESSION OF SLOTTED NOZZLE WITH JET VELOCITY AND SECONDARY AIR ACCESS	D6-20609
CHECK						
APPD						FIG. 10
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 32



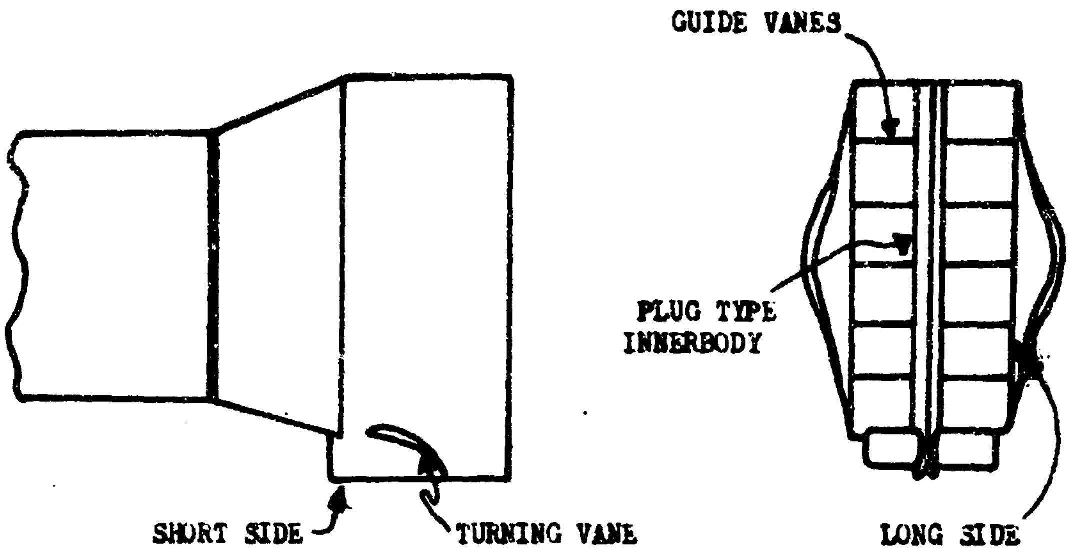
1500' SIDELINE
T = 1500° F
P.R. = 1.8
● NO BLOCKING
▲ FULLY BLOCKED

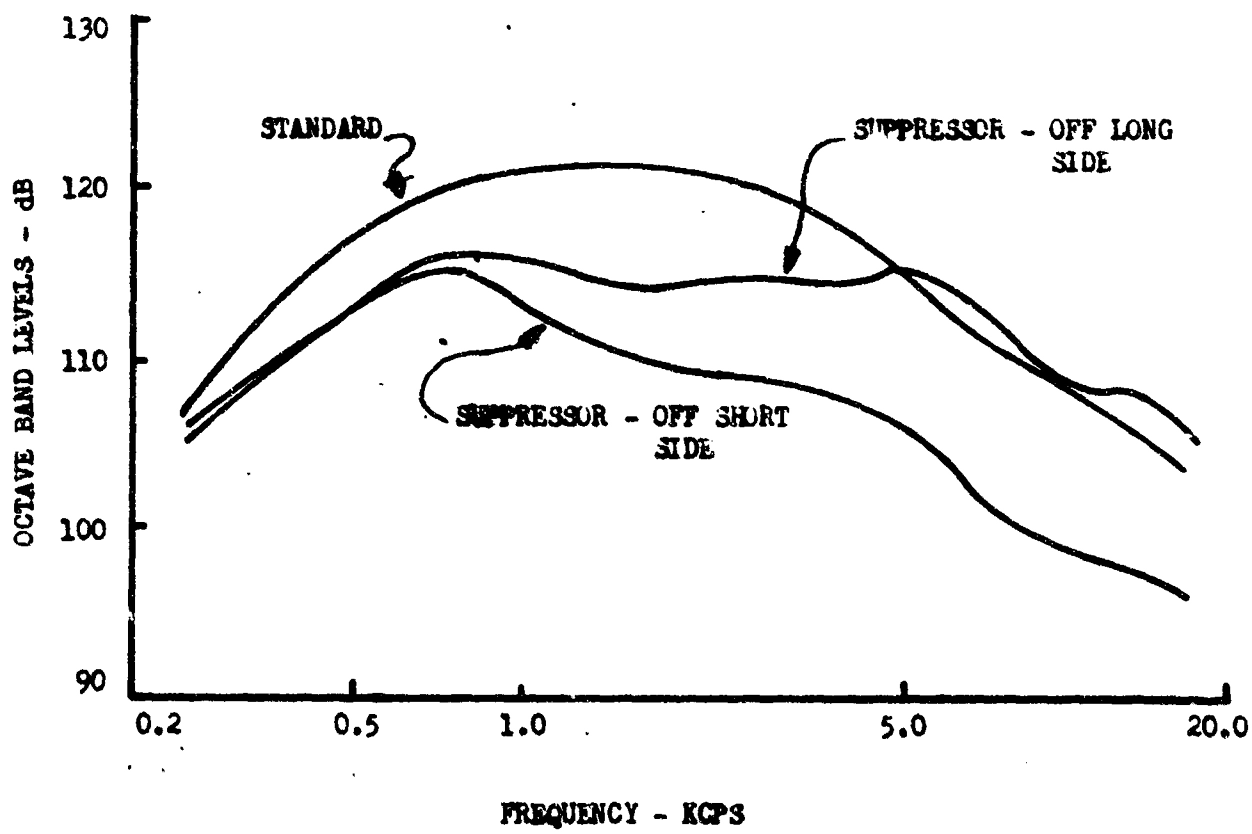
CALC			REVISED	DATE	SPECTRA OF SPL SUPPRESSION OF SLOTTED NOZZLE FOR FULLY VENTILATED AND FULLY BLOCKED SECONDARY AIR ACCESS	D6-20609
CHECK						FIG. 11
APPD						
APPD					THE BOEING COMPANY	PAGE 33



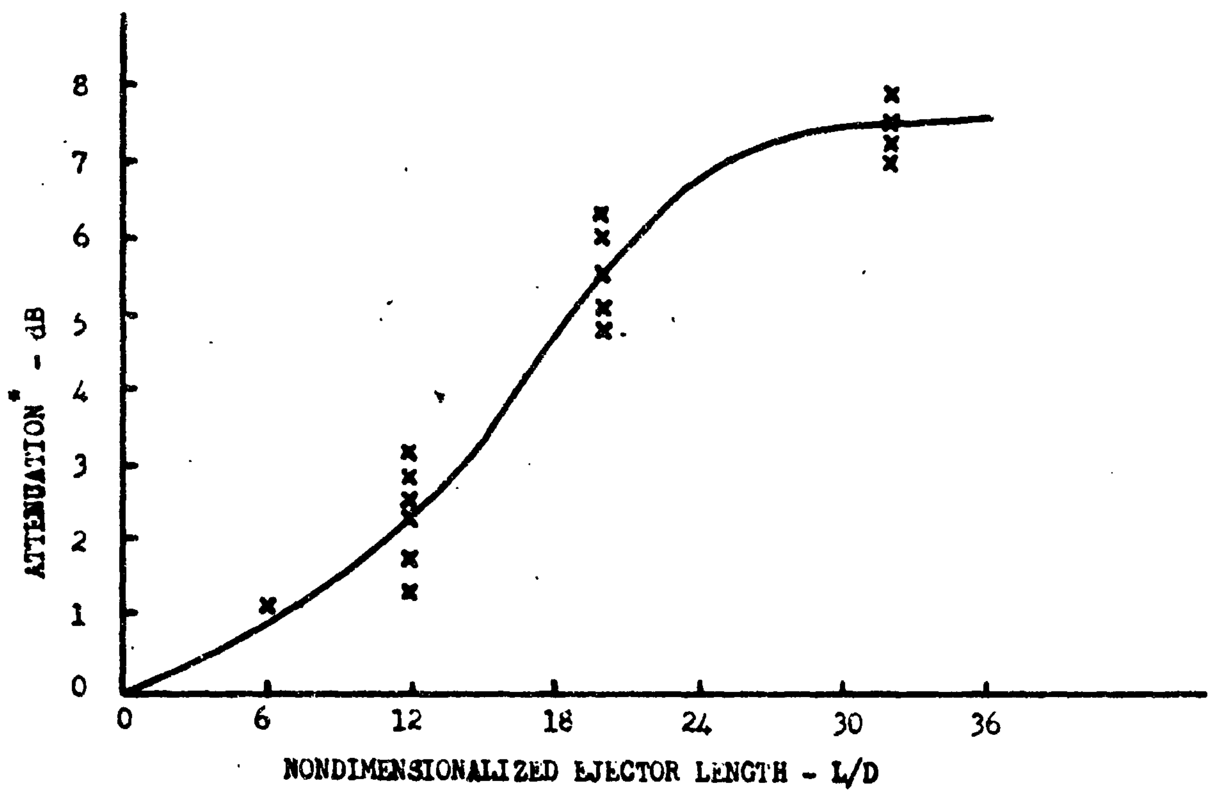
P.R. = 2.2
T = 1040° F
A.R. = 5.7
θ = 45°

CALC			REVISED	DATE	SPL SPECTRA FROM MULTITUBE NOZZLES WITH INCREASING NUMBER OF TUBES	D6-20609
CHECK						FIG. 12
APPD						
APPD					THE BOEING COMPANY	PAGE 34



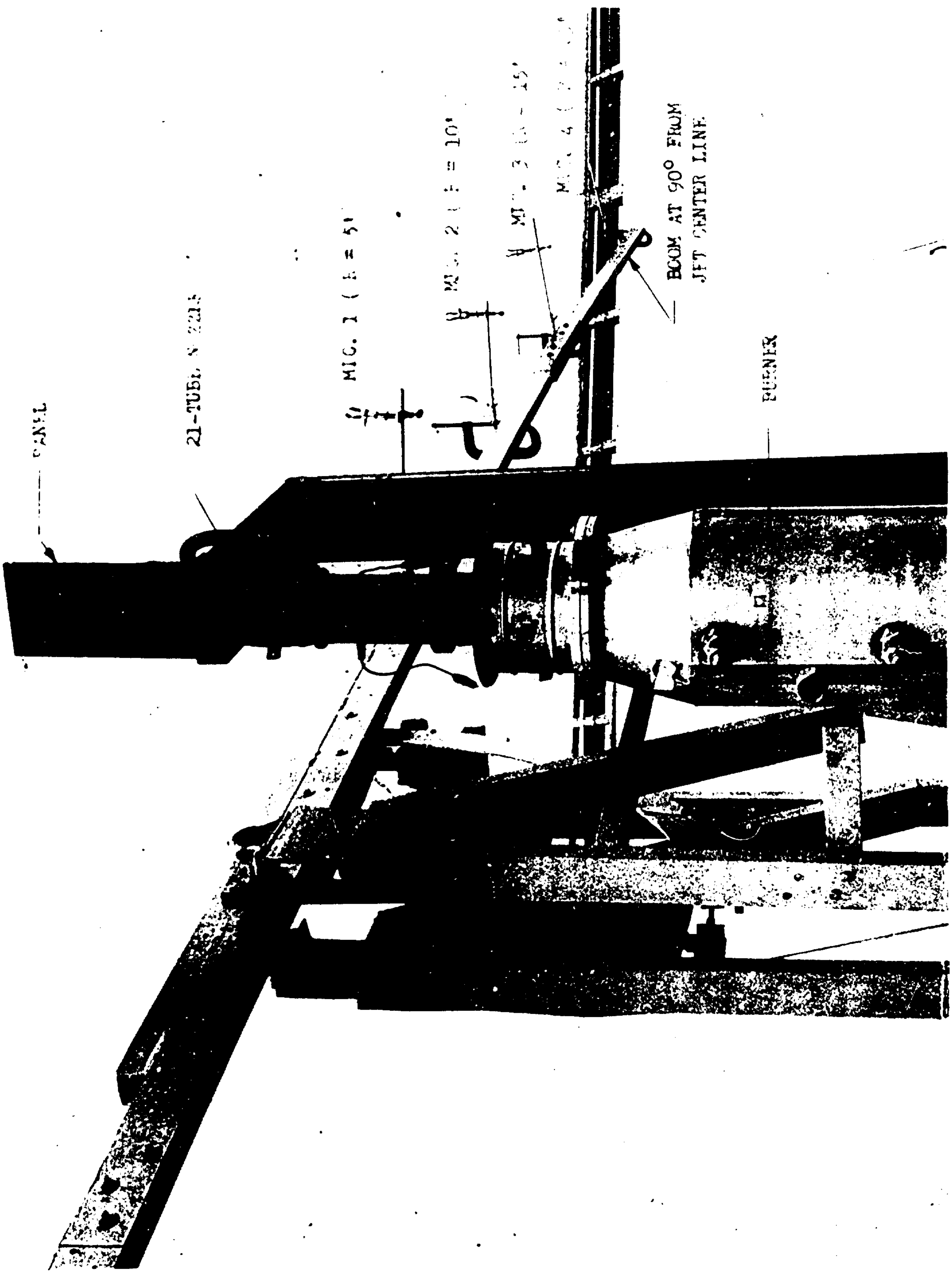


CALC			REVISED	DATE	SPL SPECTRA FROM RECTANGULAR NOZZLE SUPPRESSOR (TYLER AND SOFRIN)	D6-20609
CHECK						FIG. 13
APPD						
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 35

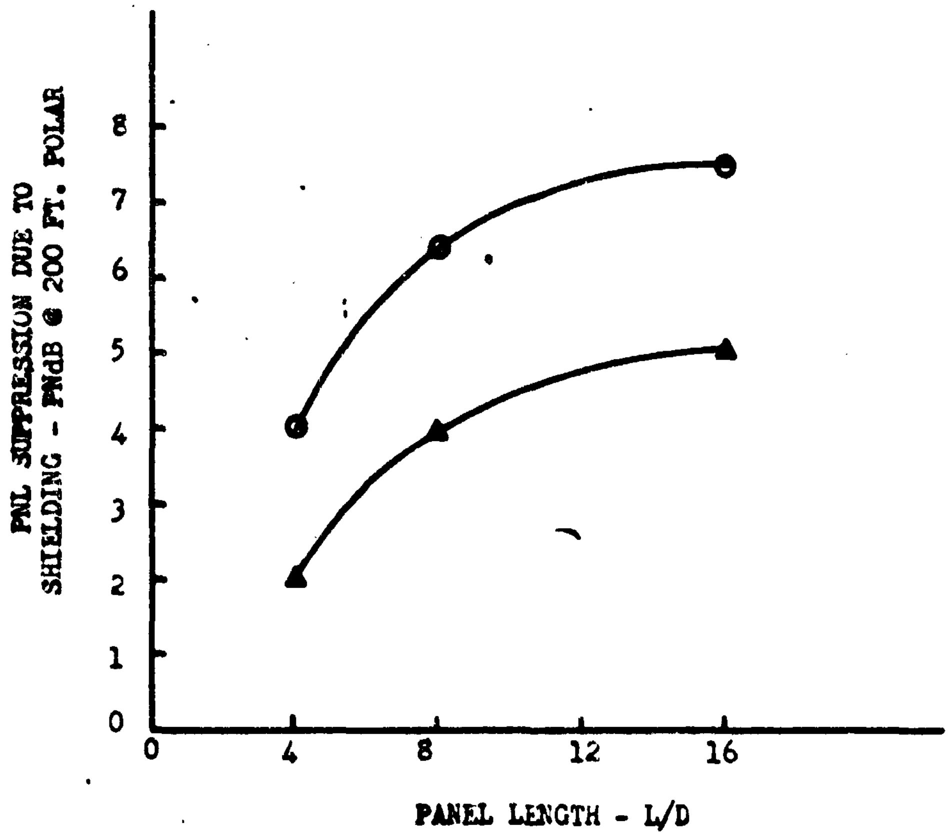


* DISCRETE FREQUENCY NOISE REMOVED

			REVISED	DATE		
CALC					VARIATION IN SPL SUPPRESSION OF EJECTORS WITH EJECTOR LENGTH (MIDDLETON)	D6-20609
CHECK						FIG. 14
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 36
APPD						

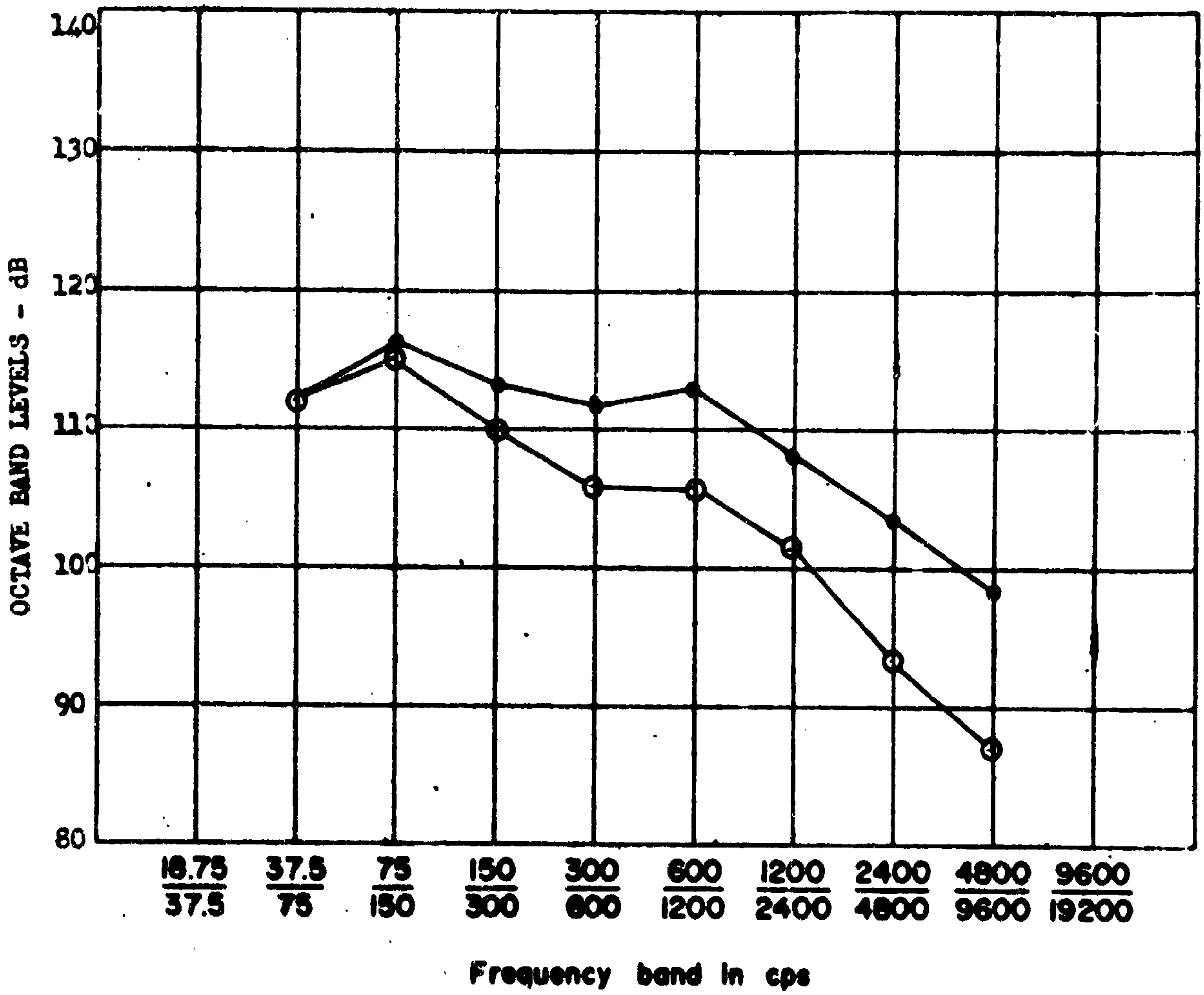


TEST SETUP FOR RECTANGULAR PANEL SHIELDING
INVESTIGATION



▲ STRD. NOZZLE, θ = 45°
○ 21 TUBE NOZZLE, θ = 70°
DIA. = 3"
P.R. = 3.13
T = 2060° R
PANEL WIDTH 2D
PANEL POSITION 1D FROM JET

CALC			REVISED	DATE	VARIATION IN PNL SUPPRESSION OF 21-TUBE AND STANDARD NOZZLES WITH LENGTH OF SHIELDING PANEL	D6-20609
CHECK						FIG. 16
APPD						
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 38

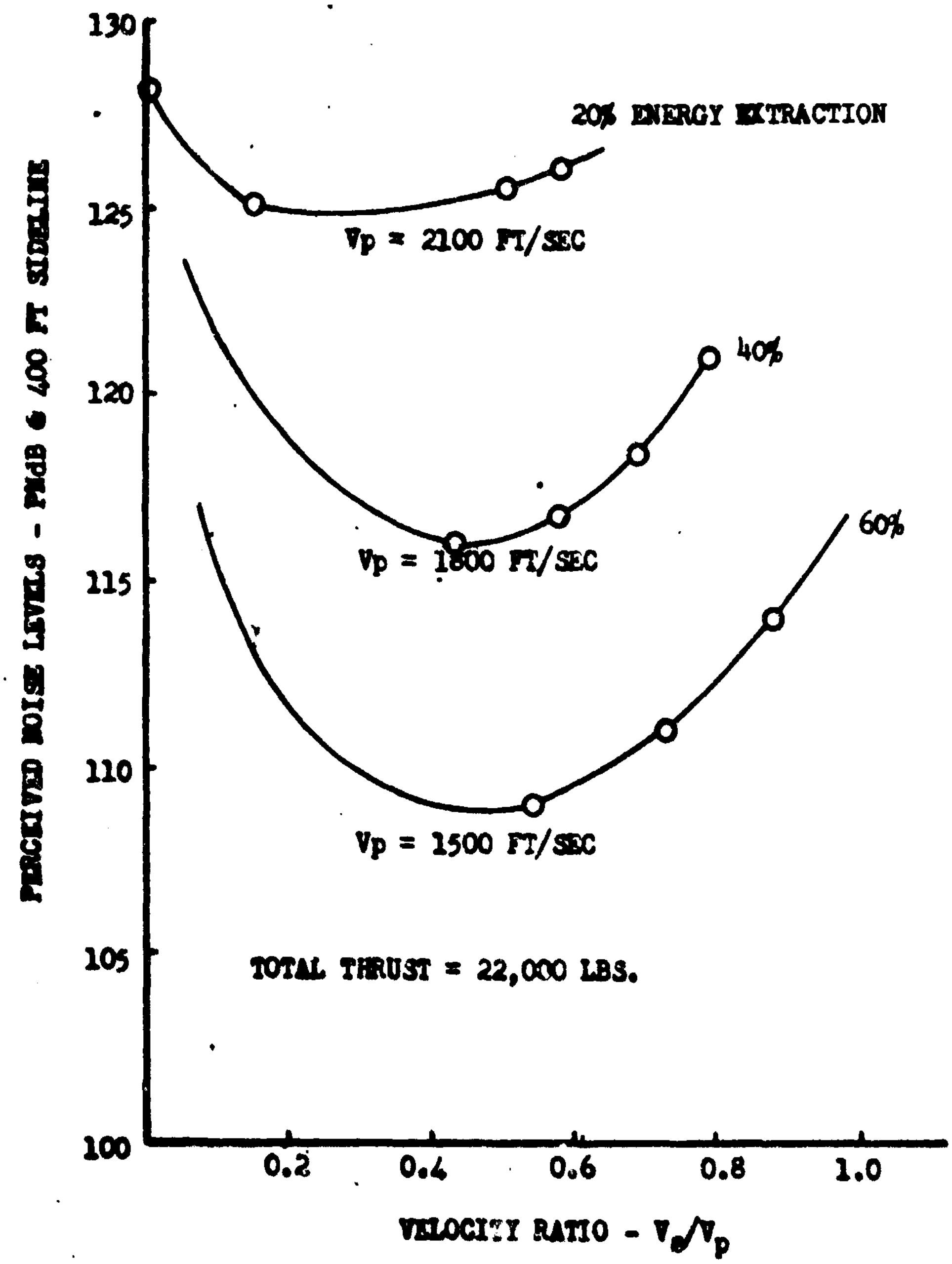


200' POLAR SPECTRA GENERATED BY A 21-TUBE C-6 SERIES NOZZLE (DIA.= 3"), 45° FROM JET EXIT CENTERLINE, JT3C-6 MAX. DRY ENGINE CONDITION S, PR = 3.13; 2060 R.

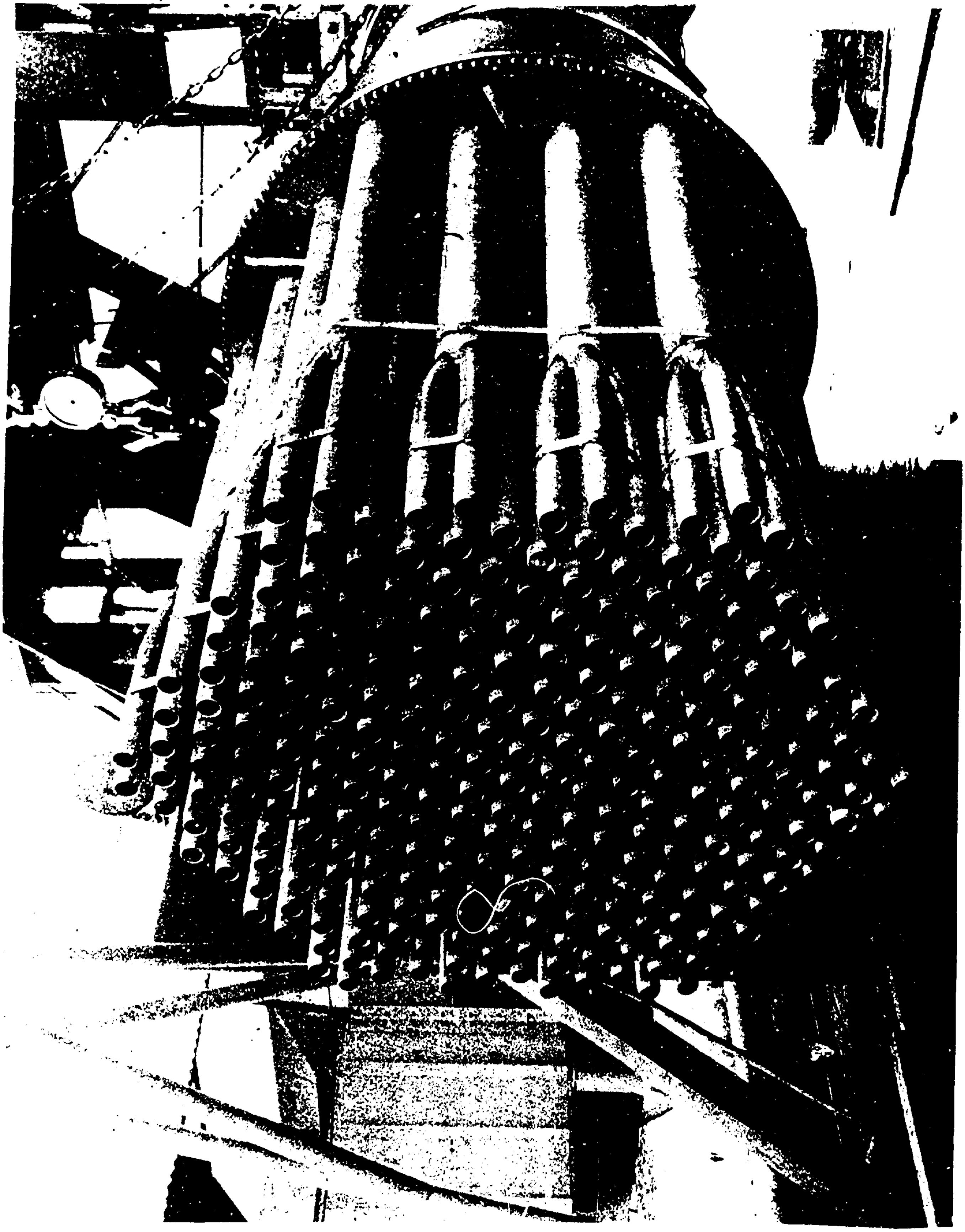
SHIELD PANEL = 0.5" THICK STEEL PANEL, L = 8D, W = 2D

● SHIELDED
● UNSHIELDED

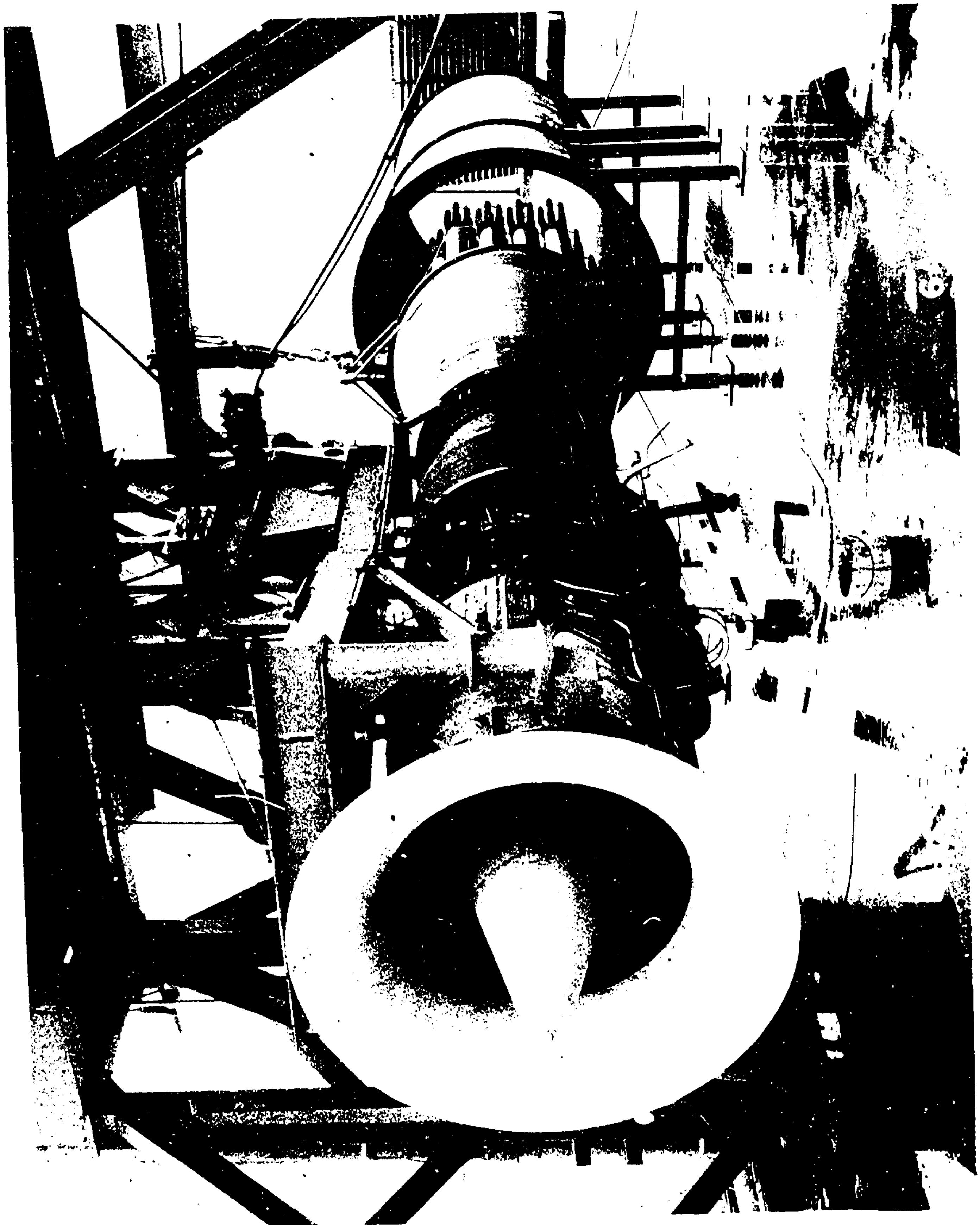
CALC			REVISED	DATE	SPL SPECTRA FROM SHIELDED AND UNSHIELDED 21-TUBE NOZZLE JET	D6-20609
CHECK						FIG. 17
APPD						
APPD					THE BOEING COMPANY	PAGE 39



CALC			REVISED	DATE	VARIATION IN PNL FROM COPLANAR, ANNULAR JETS WITH BY-PASS RATIO AND VELOCITY RATIO	D6-20609
CHECK						FIG. 18
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 40
APPD						

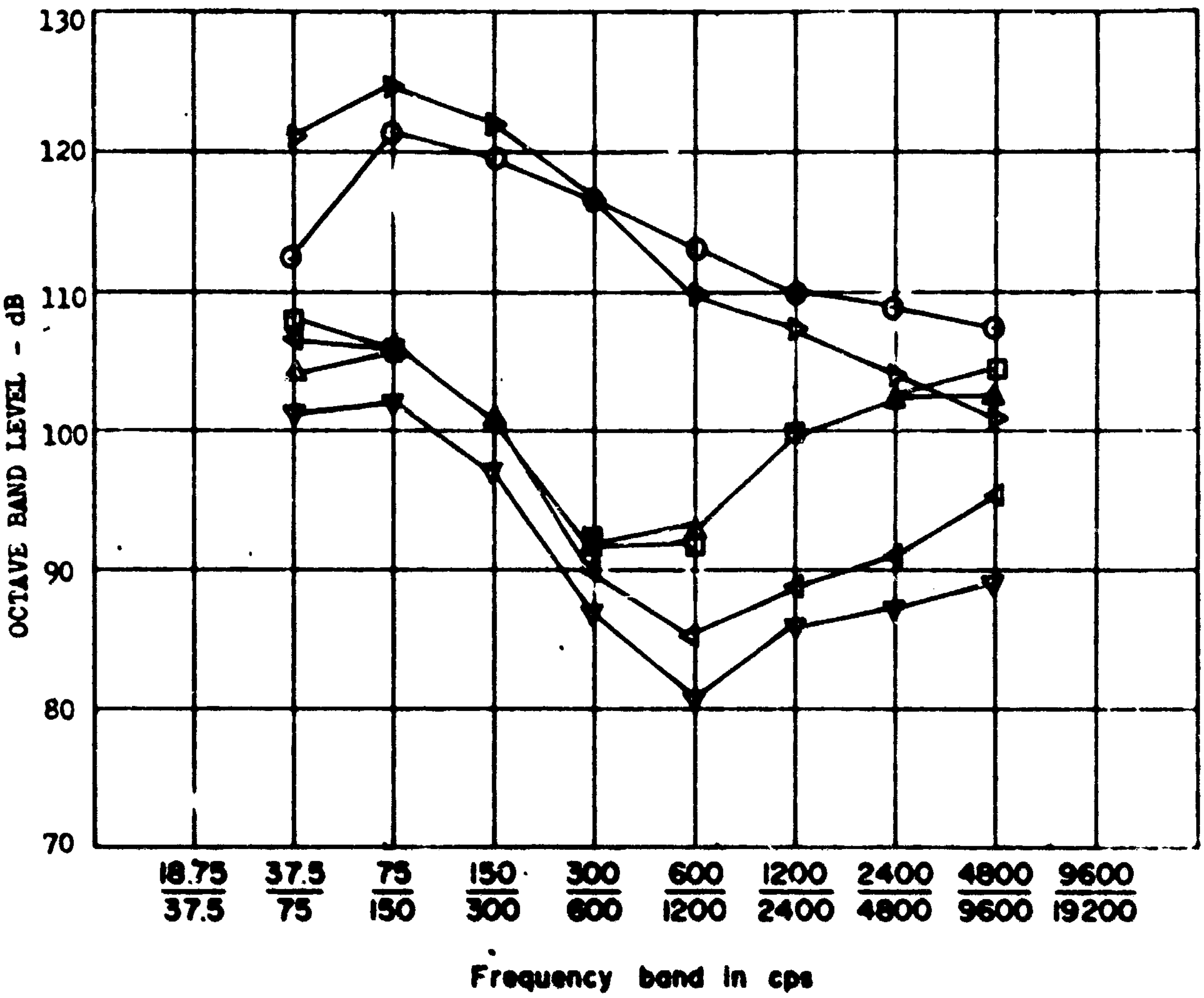


259-TUBE MIXING NOZZLE [illegible]



25[illegible]-TUBE MIXING NOZZLE [illegible]
WITH 12 FT. ACOUSTICALLY LINED SHROUD

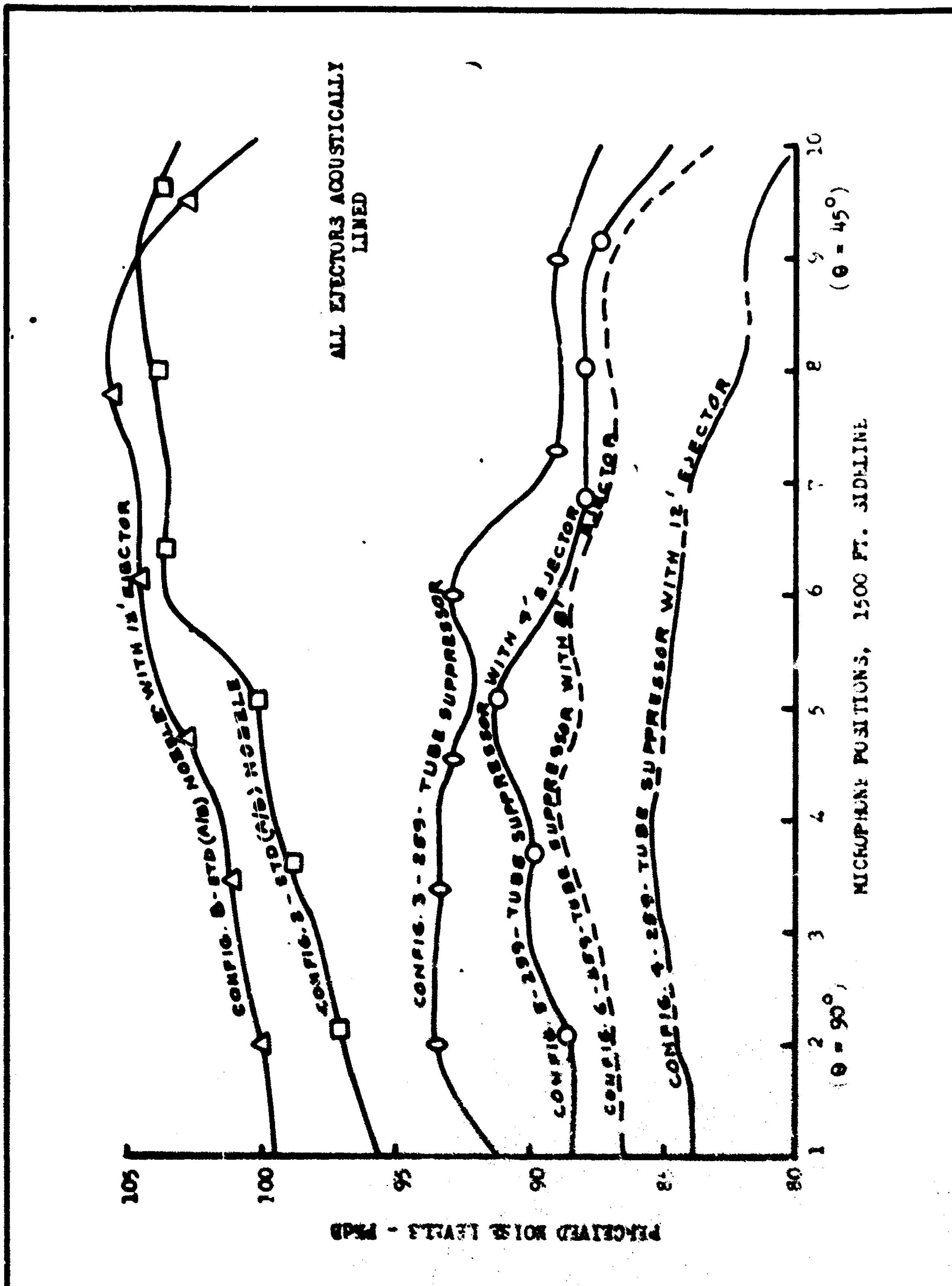
[illegible]



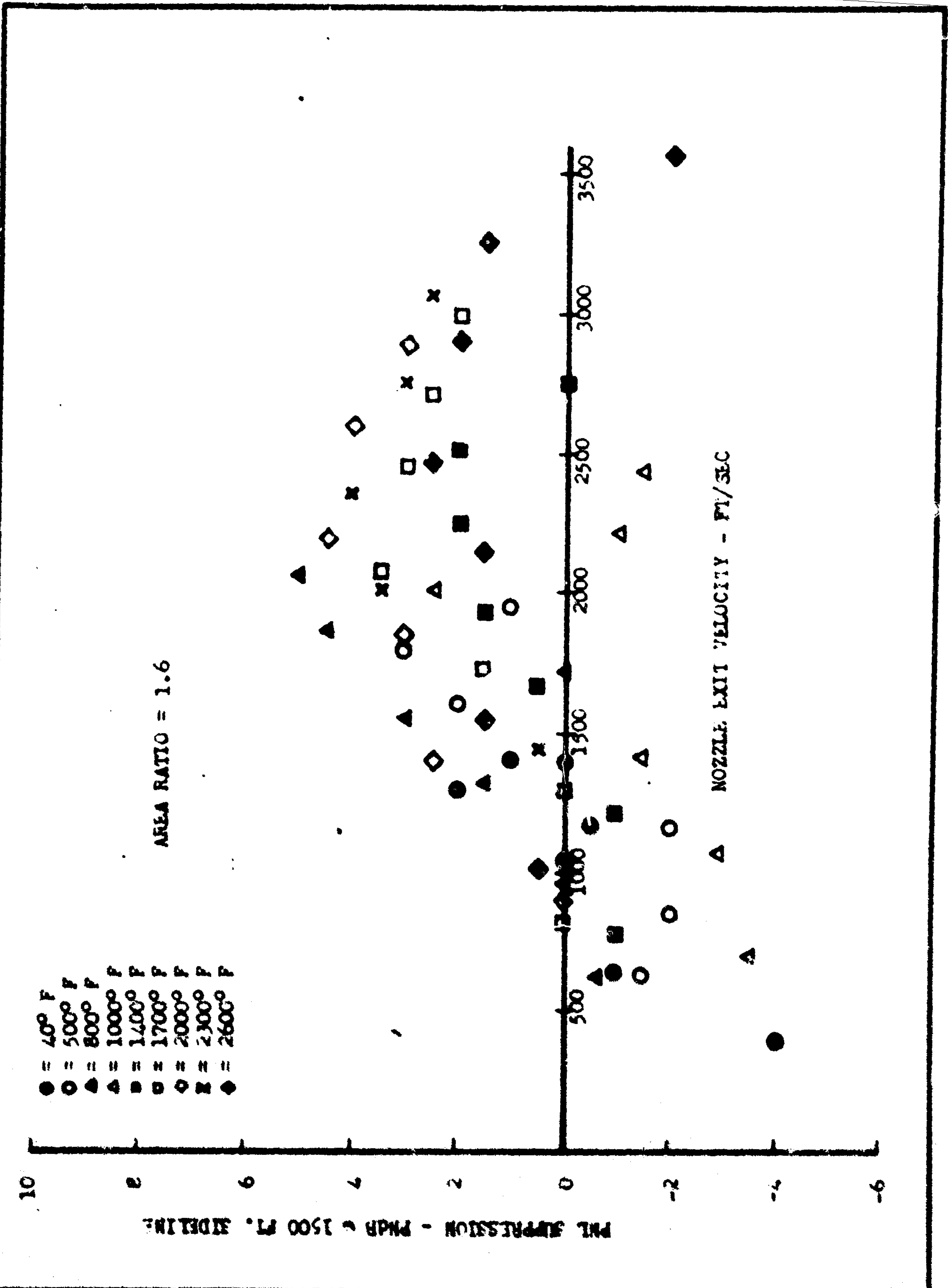
$\theta = 49^{\circ}$
1500 FT. SIDELINE

● = STANDARD NOZZLE
▲ = 259-TUBE NOZZLE
▼ = 259-TUBE WITH 12' LINED SHROUD
▶ = STD. NOZZLE WITH 12' LINED SHROUD
◀ = 259-TUBE WITH 8' LINED SHROUD
■ = 259-TUBE WITH 8' BARE SHROUD

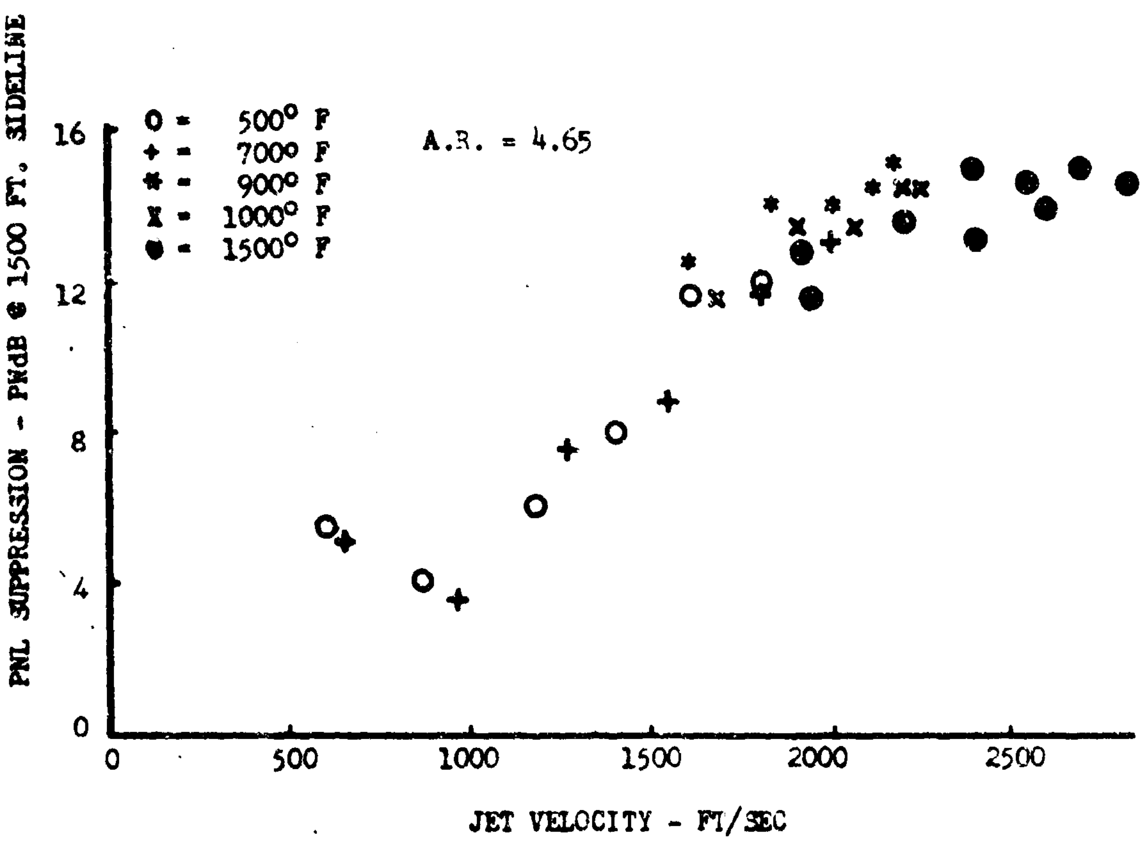
CALC			REVISED	DATE	SPL SPECTRA FROM 259-TUBE NOZZLE SUPPRESSOR WITH AND WITHOUT SHROUDS	D6-20609
CHECK						FIG. 21
APPD					THE BOEING COMPANY	PAGE 43
APPD						



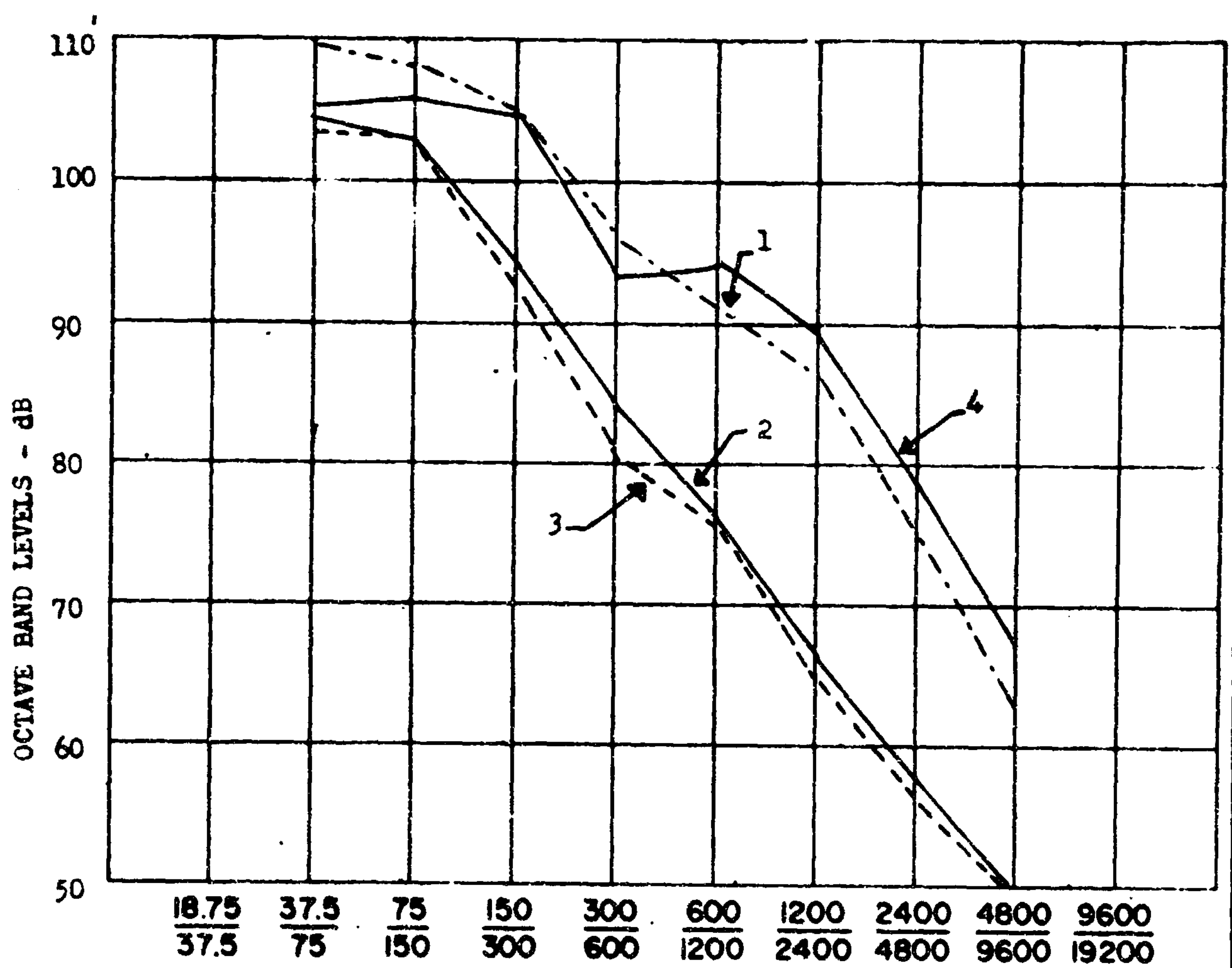
CALC			REVISED	DATE	VARIATION IN PNL ALONG 1500 FT. SIDE-LINE FOR 259-TUBE SUPPRESSOR CONFIGURATIONS	D6-20409
CHECK						FIG. 22
APPD						
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 44



CALC			REVISED	DATE	VARIATION IN PNL SUPPRESSION OF 6-LOBE GREATREX NOZZLE WITH JET VELOCITY AND TEMPERATURE	D6-20609
CHECK						FIG. 23
APPD						
APPD					THE BOEING COMPANY RENTON WASHINGTON	PAGE 45



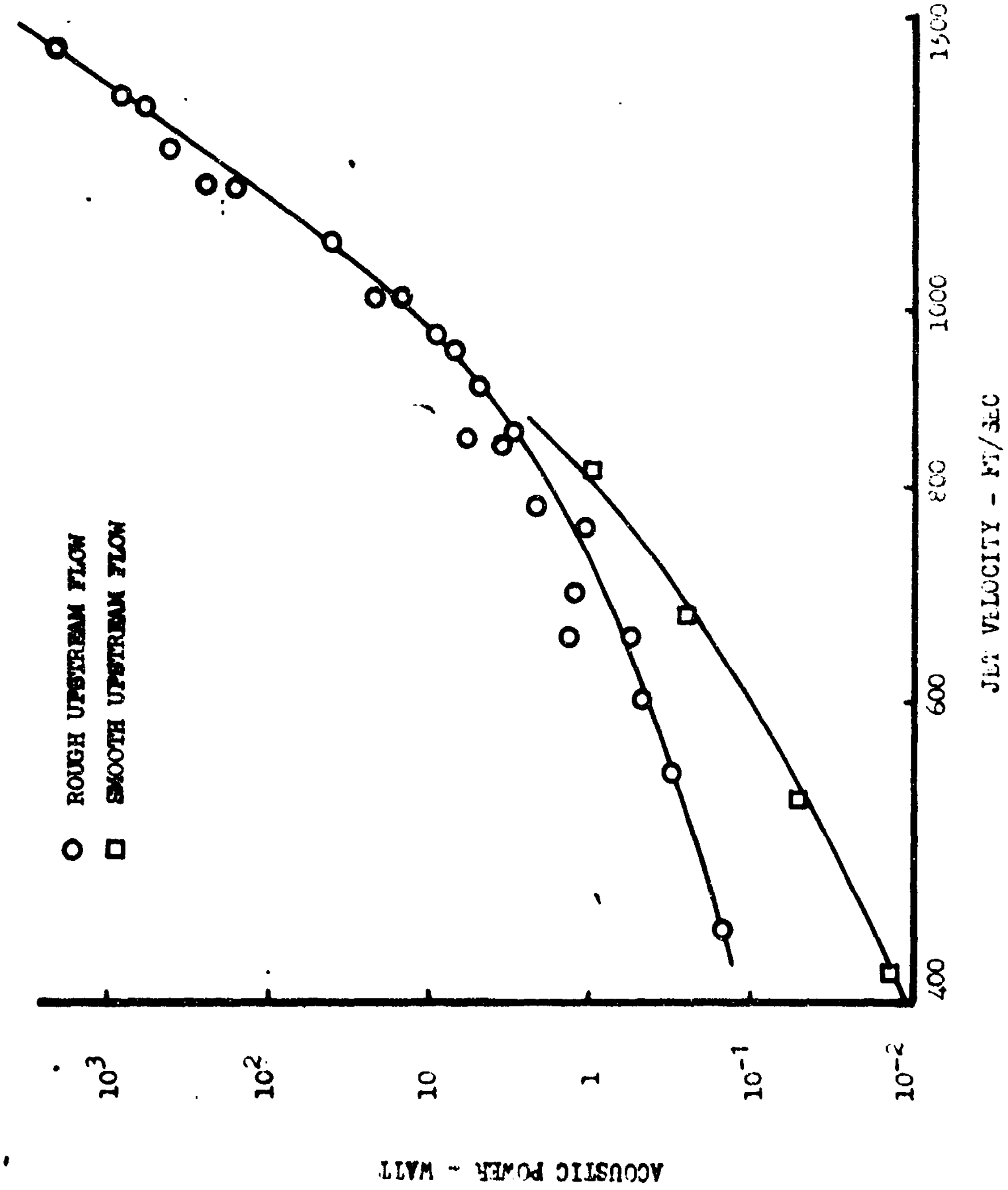
CALC			REVISED	DATE	VARIATION IN PNL SUPPRESSION OF 37-TUBE, GREATREX ENDED MIXING NOZZLE WITH JET VELOCITY AND TEMPERATURE.	D6-20609
CHECK						FIG. 24
APPD						
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 46



UNSUPPRESSED AND SUPPRESSED JET NOISE SPECTRA - 1500 FT. SIDELINE

1 ...... ROUND CONVERGENT NOZZLE - BASELINE
2 ...... ROUND CONVERGENT NOZZLE WITH E3 EJECTOR, 8-3.6" WIDE CHUTES, 40% PENETRATION
3 ...... ROUND CONVERGENT NOZZLE WITH E3 EJECTOR, 8-3.6" WIDE CHUTES, 50% PENETRATION
4 ...... ROUND CONVERGENT NOZZLE - BARE EJECTOR

CALC			REVISED	DATE	SPL SPECTRA FROM ROUND CONVERGENT NOZZLE JET WITH CHUTED EJECTOR CONFIGURATIONS	D6-20609
CHECK						FIG. 25
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 47
APPD						



			REVISED	DATE		
CALC					VARIATION IN ACOUSTIC POWER OUTPUT WITH JET VELOCITY AND UPSTREAM FLOW CONDITIONS	D6-20609
CHECK						FIG. 26
APPD						
APPD					THE BOEING COMPANY RENTON, WASHIN	PAGE 48

TD 979 0-86   6 7000